Motor Imagery
A Backdoor to the Motor System After Stroke?

Nikhil Sharma, MB, ChB, MRCP(UK); Valerie M. Pomeroy, PhD; Jean-Claude Baron, MD, FRCP, FmedSci

Background and Purpose—Understanding brain plasticity after stroke is important in developing rehabilitation strategies. Active movement therapies show considerable promise but depend on motor performance, excluding many otherwise eligible patients. Motor imagery is widely used in sport to improve performance, which raises the possibility of applying it both as a rehabilitation method and to access the motor network independently of recovery. Specifically, whether the primary motor cortex (M1), considered a prime target of poststroke rehabilitation, is involved in motor imagery is unresolved.

Summary of Review—We review methodological considerations when applying motor imagery to healthy subjects and in patients with stroke, which may disrupt the motor imagery network. We then review firstly the motor imagery training literature focusing on upper-limb recovery, and secondly the functional imaging literature in healthy subjects and in patients with stroke.

Conclusions—The review highlights the difficulty in addressing cognitive screening and compliance in motor imagery studies, particularly with regards to patients with stroke. Despite this, the literature suggests the encouraging effect of motor imagery training on motor recovery after stroke. Based on the available literature in healthy volunteers, robust activation of the nonprimary motor structures, but only weak and inconsistent activation of M1, occurs during motor imagery. In patients with stroke, the cortical activation patterns are essentially unexplored as is the underlying mechanism of motor imagery training. Provided appropriate methodology is implemented, motor imagery may provide a valuable tool to access the motor network and improve outcome after stroke. (Stroke. 2006;37:000-000.)

Key Words: magnetic resonance imaging, functional imaging, recovery of function, rehabilitation, stroke, tomography, emission computed tomography, Laterality Index, is associated with better recovery (see reviews by Ward and Cohen,6 Calautti and Baron9). Moreover AMT can result in both cortical reorganization and improved motor performance. Specifically in the chronic stage of stroke, CIT-like procedures can increase ipsilesional premotor and somatosensory cortex activation,6 whereas AMT can result in increases in ipsilesional M1 activation with a positive Laterality index shift.7 The idea is therefore emerging that “forcing” the use of the idle motor network, particularly M1, promotes long-term recovery, provided M1 is present and not isolated from the anterior horn cell.

Nevertheless, AMT has limitations; rodent models suggest CIT should be restricted during the early phase of stroke because it may result in infarct expansion,4 although this has not been encountered clinically.9 Difficulties implementing CIT in the clinical setting have resulted in a modified CIT protocol.10 However, poor motor performance still excludes almost 4 of 5 otherwise eligible subacute stroke patients from CIT.11 Attempts to bridge the period of poor motor performance by combining
different AMTs, such as electromyography-triggered neuromuscular stimulation and modified CIT,\textsuperscript{2,13} have produced unconvincing results with some severely affected subjects verbalizing frustration.

Alternative strategies such as passive mobilization can be used in persons with hemiplegia to access the motor system although it produces mainly proproceptive input to motor pathways.\textsuperscript{14} Yet, in healthy subjects passive mobilization neither improves performance nor induces the cortical plasticity shown with active movement, supporting a key role for voluntary drive in motor learning and neuro-rehabilitation.\textsuperscript{15}

In principle a therapy based on attempted movement is conceivable because it combines both M1 activation\textsuperscript{16} and voluntary drive. The authors are unaware of any published trials that use attempted movement as a rehabilitation invention; this perhaps reflects the practical difficulties in avoiding patient frustration and fatigue.\textsuperscript{12} Moreover, in subjects with hemiplegia, attempted movement is likely to be complicated by proximal or undesirable movement, and furthermore there would be no way to assess compliance (see below). Overall, the clinical uses of AMT in stroke are limited by their dependence on a degree of motor performance.

Motor imagery represents an intriguing new “backdoor” approach to accessing the motor system and rehabilitation at all stages of stroke recovery.\textsuperscript{17} Unlike active and passive motor therapies, motor imagery, in principle, is not dependent on residual function but still incorporates voluntary drive. Importantly, in the primate, M1 is directly involved in motor imagery as suggested by direct cellular recordings.\textsuperscript{18} In patients with stroke, motor imagery may therefore provide a substitute for executed movement as a means to activate the motor network.

Additional parallels between motor imagery and executed movement are worth mentioning; there is close temporal coupling between motor imagery and executed movement, i.e., the time taken to mentally perform an action closely mirrors the executed movement.\textsuperscript{19} During imagined movement, the reduction in accuracy with increasing speed (i.e., Fitt Law) is maintained\textsuperscript{20} and the asymmetry between dominant and nondominant hand is also preserved.\textsuperscript{21} Motor imagery produces similar autonomic changes as executed movement, with significant increase in heart and respiratory rates.\textsuperscript{22,23,24} Nevertheless, these principles can be disrupted by structural lesions in specific brain areas,\textsuperscript{25} the implications of which will be discussed later.

In athletes, a structured program of motor imagery movement, motor imagery training, can lead to an improvement in performance. The effects are independent of subclinical muscle activation.\textsuperscript{26} Perhaps unsurprisingly, motor imagery training produces less practical improvement compared with physical training.\textsuperscript{27} Although widely used in conjunction with physical training, motor imagery training can independently improve motor performance and produce similar cortical plastic changes,\textsuperscript{28} providing a useful alternative when physical training is not possible.

As will be discussed, a few early studies suggest that motor imagery training may improve functional recovery after stroke.\textsuperscript{29–33} However, how effective it is and in what setting it is best used remains unclear and will form the second section of this review. But in order to effectively target the correct patient population it is imperative to understand how motor imagery training may work, and hence how motor imagery allows access to the motor network. It is widely assumed that motor imagery activates similar pathways as executed movement,\textsuperscript{34} but as will be seen there are some important differences. Particular attention will be given to whether motor imagery activates M1 because this would imply greatest efficiency, although as will be discussed effects on nonprimary motor areas may also provide gains.

This systematic review of the functional imaging and motor imagery training literature will focus on hand function, because of the lateralized and large cortical representation as well as the obvious key importance of the hand in activities of daily living, and will consist of 4 sections: the first will briefly discuss general cognitive considerations, particularly when investigating motor imagery in the context of structural lesions and relevant methods of assessment; the second will review studies investigating the effectiveness of motor imagery training at restoring upper-limb motor function after stroke; the third will address the cortical network activated during motor imagery in healthy subjects and the potential implications for patient selection. In the fourth section the motor imagery functional imaging studies in patients with stroke will be reviewed. Finally, the results will be discussed and summarized, concluding with suggestions for future research.

**Cognitive Considerations**

Motor imagery can be defined as a dynamic state during which the representation of a specific motor action is internally reactivated within working memory without any overt motor output, and that is governed by the principles of central motor control.\textsuperscript{19,20,35} Operationally, this can be considered as occurring from the 1st person perspective.\textsuperscript{36} The interested reader is referred to dedicated reviews on the cognitive neuroscience theories of motor imagery.\textsuperscript{36,37}

**Motor Imagery in Stroke**

Motor imagery is an integral part of the wider motor system that can be represented by internal models or programs, which develop over time and are consistently changing.\textsuperscript{38} In chronic disease states temporal coupling is often preserved; in Parkinson disease the asymmetrical bradykinesia is mirrored during motor imagery,\textsuperscript{39} as is the performance in the chronic fatigue syndrome.\textsuperscript{40} However, in patients with stroke it is important to consider both the ability to perform motor imagery accurately and temporal coupling because, depending on the site and extent of the stroke, either or both may be affected.

Because the parietal lobe is involved in the preservation and generation of a kinaesthetic model,\textsuperscript{41} it is perhaps not surprising that parietal damage can reduce motor imagery accuracy.\textsuperscript{42–43} By excluding subjects with parietal or premotor lesions, Johnson\textsuperscript{44} used a prehensile task to suggest that both subacute and chronic hemispheric patients\textsuperscript{45} may still perform motor imagery. Moreover, the authors even suggest that subjects with chronic stroke may be more accurate during motor imagery with the affected limb, a “hemiplegic advantage”.

Late disruption of M1 (hand area) by transcranial magnetic stimulation (TMS) can also reduce motor imagery accuracy and increases response time during the mental rotation of
hands but not feet; the authors suggest that M1 is not only involved in motor imagery but is required. Conversely, others have reported that M1 is not necessary to perform motor imagery, whereas direct stimulation of M1 via an implanted electrode array may not disrupt motor imagery accuracy but increase response time.

Temporal uncoupling may occur after either parietal or frontal lobe damage but can be preserved after cerebellar stroke. In partially recovered patients, Malouin et al speculated that stroke could result in temporal uncoupling of the nonaffected limb while being preserved in the affected limb. However, the authors acknowledge that this unexpected finding could be explained by the extensive strokes included in the study causing either cortical–cortical disruption of the motor imagery network or a deficit in working memory, which in itself may reduce the effectiveness of motor imagery training. However, Sabate et al reported that temporal coupling can be preserved after stroke.

Despite the limited samples and the wide variety of lesion location in these studies, overall, the ability to perform motor imagery may be preserved after stroke, but it appears that both accuracy and temporal coupling can be disrupted. We have referred to this as chaotic motor imagery.

Chaotic motor imagery can be defined as an inability to perform motor imagery accurately or if having preserved accuracy, demonstration of temporal uncoupling. Further characterization of motor imagery performance in subjects unable to perform accurately or with temporal uncoupling is likely to produce incongruent results. Chaotic motor imagery may be limb-specific, affecting distal but not proximal movement probably attributable to differences in cortical organization. Although we primarily use the term “chaotic motor imagery” here to designate inability to perform motor imagery in people with central nervous system damage, it is possible that it also applies to a small percentage of the normal population.

Motor Imagery: Assessment of Ability, Performance and Compliance

It follows from the definition of motor imagery that because of its concealed nature, a subject may surreptitiously use alternative cognitive strategies that, if not screened for, could confound investigations and produce conflicting results. Applied to the normal population these alternative strategies can be distilled into 4 components: the inability to perform motor imagery or inaccuracy; a simple failure to comply; the concealed use of alternative strategies such as counting or visual imagery; and a failure to suppress movement. In addition, when applied to the study of patients with stroke, chaotic motor imagery should be considered.

In order to select appropriate subjects for clinical studies, particularly functional imaging and motor imagery training, a dichotomic approach to motor imagery, able versus unable, is imperative; however, it should be noted that motor imagery is a complex cognitive process. As such, important information which further characterizes the quality and vividness of the motor imagery effected by the enrolled subjects performed should be obtained.

Inability to Perform Motor Imagery

When cognitive screening for the ability to perform motor imagery accurately is applied to a normal population, a small fraction of subjects will fail the assessment. Historically, questionnaires (eg, Mental Imagery Questionnaire (MIQ)) were used which were aimed primarily at athletes, subjectively selecting those who were skilled at motor imagery. The questionnaire requires subjects to perform complex tasks physically and then using motor imagery, after which subjects rate their performance on both a kinaesthetic and visual scale. Because of the difficulties in performing the tasks, a modified MIQ has been produced which comprises of simpler gestures, though it still does not provide objective evidence of motor imagery ability.

An interesting alternative is the Controllability of Motor Imagery Scale: subjects follow a series of instructions each specifying a single mental movement of a limb; at the end the subject must assume the position produced by the combination of movement. Those unable to do so are excluded, providing objective evidence of motor imagery ability. Although the use of alternative strategies such as visual imagery is not addressed, it remains a more useful assessment than the MIQ.

Perhaps the most appropriate method to assess motor imagery accuracy is to use a prehensile task, similar to Johnson because this provides objective evidence and intrinsically activates the motor imagery network.

Simple Failure to Comply

Unlike executed movement paradigms during which compliance can be checked by observation of the task, motor imagery is concealed and requires more complex monitoring. Hanakawa used visually presented numbers to “guide” subjects through a prelearned finger-tapping sequence. In this procedure, subjects are instructed which finger to begin and then presented a number; the subject then moves the corresponding steps through the sequence, and at end of block is asked to confirm the position. Although this method does provide evidence of compliance, it encourages the use of alternative techniques, particularly counting.

We have used a variant of this method; the motor imagery task is paced and unexpectedly stops and the subject has to confirm their position. Although this technique would be pragmatically difficult to include into a motor imagery training program, it is of particular interest in functional imaging studies when it can be incorporated into the paradigm, with those who fail to correctly confirm being excluded. Regardless of these details, the task must be of sufficient complexity to contain a number of possible positions so a correct response is unlikely to be attributable to chance.

A similar method is the application of mental chronometry, ie, (re)action times for instance; the number of foot taps in various time blocks can be compared with the number of imagined taps. This method is particularly useful during motor imagery training, providing an objective assessment of compliance; however, in the way it has been used so far it is unable to exclude a noncompliant individual.

Nonetheless, it remains that all of these tasks can easily be solved by the use of alternative strategies such as counting, visual imagery or 3rd person imagery.
Concealed Use of Alternative Strategies
Because the aim of motor imagery is to activate the motor networks, it is crucial that subjects perform the mental task from the 1st person perspective, in contrast to 3rd person perspective or visual imagery.66 Likewise, they should also be instructed not to count, as also by doing so a subject could fool an exclusion criteria based on confirmation of position. This has not been addressed in the literature but a form of objective assessment is clearly needed.

Failure to Suppress Movement
Several methods can be used to monitor overt or covert movement during motor imagery. The electromyogram (EMG) has been used during training before the functional imaging sessions62,63 to ensure subjects do not move. This presents practical challenges during motor imagery training and functional MRI (fMRI), although it is possible in the latter58 and during positron-emission tomography (PET) studies. Close inspection of the subject is the simplest way to highlight overt movement, though once again this is difficult in the MRI bore and small amplitude movements may be missed. Alternatively, a dynamometer,64 an accelerometer65 or goniometer66 could be used in the fMRI session but not easily during motor imagery training. Specifically for the fMRI sessions, video observation may present an alternative method. We have successfully used fiber-optic MR-friendly gloves.59

Chaotic Motor Imagery
The identification of subjects performing chaotic motor imagery is not addressed by any published assessments, yet this is possibly a very important confound in both the interpretation of previous studies50,51 and the application of motor imagery training and motor imagery to patients with stroke. Crucially, the potential screening tools discussed above would not be suitable for subjects performing chaotic motor imagery. Moreover, including subjects who perform chaotic motor imagery into a motor imagery training program may dilute any positive affects. Furthermore, a lack of more general cognitive ability (dysphasia, dementia, neglect or inattention) would make an assessment of motor imagery ability very difficult or impossible.

For these reasons at this stage, theoretically a subject whose stroke is subcortical and does not involve M1 or the parietal lobe are likely to benefit the most from early motor imagery training. However, it is possible that many other factors may influence motor imagery training, such as gender, handedness, affected hemisphere, dysphasia, precise lesion location and time elapsed since stroke.

Review of the Literature
Motor Imagery Training Effectiveness
We will review studies investigating the effectiveness of motor imagery training at restoring motor function after stroke.

Inclusion Criteria
A systematic literature search using the electronic database on PubMed was performed. Only studies that focus exclusively on motor imagery of the upper-limb function and rehabilitation after stroke will be considered. Although other articles have been published67–75 only 5 fulfilled the criteria.29,30–33

Clinical Data
Details of the number and characteristics of subjects included in the 5 primary studies are given in Table 1. Age and gender ratio are similar across studies but there are large differences in the time since stroke.

Lesion location and affected hemisphere is poorly reported across all the studies, as is any clinical classification or description of the stroke. Motor function is not always described in sufficient detail; of note is that all the studies excluded subjects with hemiplegia. General cognitive assessment was performed in 4 studies,30–33 using the Mini Mental State Examination. It is likely that with such a wide range of cognitive ability combined with a lack of topographic data, a portion of subjects will have been performing chaotic motor imagery.

TABLE 1. Upper-Limb Motor Imagery Training Studies: Demographics

<table>
<thead>
<tr>
<th>Study</th>
<th>Subject No. and Gender</th>
<th>Mean Age, y</th>
<th>Mean TSS, mo</th>
<th>Stroke Classification/Location</th>
<th>Affected Hemisphere L:R</th>
<th>Motor Function</th>
<th>Cognitive Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page (2001)29</td>
<td>13 (10 M)</td>
<td>64.6</td>
<td>6.5</td>
<td>N/A</td>
<td>N/A</td>
<td>FMA=29</td>
<td>ARAT 24.7</td>
</tr>
<tr>
<td>Crosbie (2004)32</td>
<td>10 (6 M)</td>
<td>63.9</td>
<td>1.3</td>
<td>7×PACS, 1×LACS</td>
<td>N/A</td>
<td>Mean MI 30</td>
<td>Mean MMSE 27 (16–30)</td>
</tr>
<tr>
<td>Dijkerman (2004)31</td>
<td>20 (14 M)</td>
<td>64</td>
<td>24</td>
<td>N/A</td>
<td>N/A</td>
<td>GS 68%</td>
<td>Barthel 95.5</td>
</tr>
<tr>
<td>Liu (2004)32</td>
<td>49 (22 M)</td>
<td>71.9</td>
<td>13.9</td>
<td>MCA territory</td>
<td>N/A</td>
<td>FIM motor score=42</td>
<td>FIM cognitive score=30.4</td>
</tr>
<tr>
<td>Page (2005)33</td>
<td>11 (9 M)</td>
<td>63.2</td>
<td>23.4</td>
<td>N/A</td>
<td>N/A</td>
<td>AOU 1</td>
<td>Modified MMSE&gt;70</td>
</tr>
</tbody>
</table>

MMSE indicates Mini Mental State Examination; TSS, time since stroke; GS, grip strength affected/grip strength non-affected; AOU, Amount of use scale; QOM, Quality of Movement scale; PACS/LACS/TACS, Bamford Clinical Classification Stroke327; FIM, Functional Independence Measure; ARAT, Action Research Arm Test; MI, Motricity Index.

<table>
<thead>
<tr>
<th>Study</th>
<th>Design</th>
<th>Background Rehabilitation</th>
<th>Specific Motor Imagery Instructions</th>
<th>Frequency of Intervention and Setting</th>
<th>Motor Imagery Intervention</th>
<th>Control Intervention</th>
<th>Outcome measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page (2001)29</td>
<td>Randomized 2 groups Motor Imagery (n=8) Control (n=5)</td>
<td>Therapy given 3 × per wk in 1-h blocks for 6 wk</td>
<td>External Visual images</td>
<td>3 time per wk twice at home for 6 wk OPD</td>
<td>After Therapy 10 min tape UL functional tasks</td>
<td>10 min After therapy 10 min tape stroke information</td>
<td>FMA Upper limb ARAT</td>
</tr>
<tr>
<td>Crobbie (2004)30</td>
<td>Replicated single-case</td>
<td>Conventional rehabilitation</td>
<td>Visualize the task</td>
<td>Daily for 2 wk In Patient</td>
<td>R&amp;G Task PP 1 attempt Motor Imagery 2 ×10 reps</td>
<td>Not controlled Subject practices independently</td>
<td>Nil N/A Morticity Index (upper limb)</td>
</tr>
<tr>
<td>Dijkerman (2004)31</td>
<td>Pseudorandomization 3 groups Motor Imagery (n=10), VI (n=5) and NI (n=5)</td>
<td>R&amp;G Task 1st person</td>
<td>Daily for 4 wk Patient’s Home</td>
<td>Motor Imagery Gp R&amp;G 1 × PP 3 × Motor Imagery</td>
<td>N/A</td>
<td>VI Group* visual pictures NI Group*</td>
<td>Trained and Untrained task (TTC &amp; errors) HPT GS</td>
</tr>
<tr>
<td>Liu (2004)32</td>
<td>Randomized 2 groups Motor Imagery (n=26), FR (n=20)</td>
<td>1-h Conventional Rehabilitation</td>
<td>Imagine his/her performance</td>
<td>Daily For 3 wk In Patient</td>
<td>Motor Imagery Gp 3 sets of 5 daily tasks</td>
<td>1 h Functional Rehabilitation Group 3 sets of 5 daily tasks</td>
<td>1 h Trained &amp; Untrained tasks FMA</td>
</tr>
<tr>
<td>Page (2005)33</td>
<td>Randomized controlled single blinded Motor Imagery (n=6) Control (n=5)</td>
<td>30 minutes therapy sessions 2 days a wk for 6 wk</td>
<td>Internal Poly-sensory images</td>
<td>Twice a wk For 6 wk OPD</td>
<td>After Therapy 30 min Motor Imagery tape UL tasks</td>
<td>30 min After therapy 30-min relaxation tape</td>
<td>MAL ARAT</td>
</tr>
</tbody>
</table>

See TABLE 1 for other abbreviations: R&G indicates reach & grasp; N/A, not reported or not applicable; UL, upper limb; MAL, Motor Activity Log; FMA, Fugl-Meyer Assessment; TTC, time to complete; OPD, out-patient department; HPT, 10 Hole Peg test; reps, repetitions; PP, physical practice; VI, visual imagery; NI, no imagery. *Groups were combined for analysis.

**Study Design, Interventions and Outcome Measures**

The details of design of the 5 studies are outlined in Table 2. Three studies29,32,33 were randomized controlled trials although sample size was not based on a power calculation. Where applicable, groups were reasonably balanced, with no significant differences in motor performance. Three studies29,32,33 used a blinded assessor to undertake the outcome measures.

All studies provided a control intervention except 130 whose replicated case design removed the need. Both the control intervention and motor imagery training were provided in addition to a background rehabilitation therapy that in 2 studies31,33 was related to the motor imagery training. Only 2 studies31,33 specifically instructed subjects to perform motor imagery; the remaining were either vague or encouraged visual imagery.

Both the control intervention and motor imagery training were balanced for frequency and duration. Across the studies the control intervention varied markedly, as did the motor imagery training; of note 1 study32 used a motor imagery training program based on the functional retraining program used as a control intervention, thus limiting inclusion to stroke patients with a degree of movement.

Outcome measures varied between studies limiting direct comparison, although all measured motor function of the paretic upper limb. In addition 2 studies31,32 used the trained task (task used in motor imagery) and an untrained task to assess outcome.

**Subject Performance**

Only 1 study29 assessed motor imagery ability using the MIQ; however, this was not used in their subsequent study.33 None of the studies assessed the use of alternative strategies, subtle movement or monitored compliance, which may be particularly relevant for instructions delivered via prerecorded tape.

**Findings**

The heterogeneity in subject characteristics, interventions and outcome measures across the 5 studies precludes any general conclusion, but overall all studies found that motor imagery training had encouraging effects on motor function compared with the control condition. One study32 found a significant advantage for the motor imagery training group for both untrained and trained tasks, maintained at 1 month, whereas another study31 found a significant advantage only for the trained task. In addition, 1 study29 demonstrated an improved outcome in the motor imagery training group (no probability value given) on the Fugl-Meyer and Action Research Arm Test scores 1 week after end of training, and another30 showed a significant change (no probability value given) in Motricity Index in 8 of 9 subjects during the intervention. Further, still another study33 confirmed a significant increase in the Action Research Arm Test immediately after training in the motor imagery training group. In addition to showing that motor imagery had positive effects on motor function, these studies also suggest that the effects might generalize beyond the tasks being trained. With only 1 study32...
following-up subjects after 1 month after the training period, it is unclear, however, whether motor imagery training is able to produce long-term gains.

Functional Imaging Studies

Healthy Subjects

A systematic search on PubMed was performed. For the purpose of this review, to explore the neural mechanism of motor imagery and allow an appropriate frame of reference, only studies that contrasted motor imagery of a hand action with rest, as opposed to another more or less complex cognitive task, will be included in this review (also see Discussion section). Furthermore, to allow meaningful comparison only articles with published stereotactic coordinates based on whole-brain voxel-based analysis of motor imagery contrasted with rest will be analyzed in detail. Although numerous studies have been published, only 59 studies fulfilled these criteria. However, 6 otherwise relevant Region of Interest (ROI)–based studies will be also commented on.

Main Studies

General Features. Demographics are given in Table 3. The objective of the studies varied; in only one study was it the primary aim to investigate the motor imagery network. Of note 1 study included subjects who were not completely right-handed; as will be seen, this is of particular relevance when considering cortical activation patterns.

Functional Imaging Paradigm. The activation task and pacing varied markedly across the studies; of note 1 study used a motor imagery task that required the subject to imagine their arm outstretched while performing the finger task. Only 1 study explicitly states that the auditory stimuli were continued during rest.

Subject Performance. Table 4 documents the methods each study used to tackle the difficult cognitive challenges. Overall, the methods used were sparse. Instructions to subjects were limited; only 1 study was specific and only 3 asked subjects not to perform visual imagery or count. All the studies except one attempted to assess motor imagery ability; however, this particular study was unique in that they monitored compliance during the imaging paradigm. This was achieved by asking subjects to confirm their position after the finger-tapping sequence during both the training and the positron-emission tomography session. Interestingly, the block duration was fixed (50 seconds) but the tapping sequence varied in length ensuring a different end position, yet whether the subject was informed of this is unclear. The remaining studies had no confirmation of performance. No study assessed alternative strategies. All studies, bar 1, monitored for subtle movement in either the task training, imaging paradigm or both.

Data Analysis. All the studies used versions of the Statistical Parametric Mapping (SPM) software, either SPM 96 or SPM 99. Two studies used random effect analysis, with the remaining using fixed effects analysis. Statistical

<table>
<thead>
<tr>
<th>Author</th>
<th>Objective of Study</th>
<th>Subject No. Gender and Handedness</th>
<th>Age Mean (Range)</th>
<th>Method</th>
<th>Activation Task (rate of external pacing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binkofski (2000)</td>
<td>Broca’s region &amp; imagery of motion</td>
<td>6 (6 M, 6 RH)</td>
<td>N/A (25–40)</td>
<td>fMRI</td>
<td>†Index finger performing double circle (0.5 Hz)</td>
</tr>
<tr>
<td>Gerardin (2000)</td>
<td>Neural networks Motor Imagery and executed movement</td>
<td>8 (5 M, 8 RH)</td>
<td>26.6 (21–35)</td>
<td>fMRI</td>
<td>**Flex/Ext of fingers (0.5 Hz)</td>
</tr>
<tr>
<td>Boecker (2001)</td>
<td>Effect of Sequence Structure</td>
<td>6 (3 M, 6 RH)</td>
<td>39</td>
<td>PET</td>
<td>Finger Tapping Sequence (1 Hz)</td>
</tr>
<tr>
<td>Naito (2002)</td>
<td>Effect of Sensory feedback on Motor Imagery</td>
<td>10 (10 M, 10 RH)</td>
<td>N/A (20–25)</td>
<td>PET</td>
<td>Wrist Flex/Ext (Not paced)</td>
</tr>
<tr>
<td>Lacourse (2005)</td>
<td>Comparing novel and skilled movement</td>
<td>54 (19 M, # 5.28)</td>
<td>24.5</td>
<td>fMRI</td>
<td>Finger tapping Sequence (selfpaced 4 Hz)</td>
</tr>
</tbody>
</table>

PET indicates positron-emission tomography; RH, right-handed.

*All of these studies used a box car design and rest as a contrast; †arm was imagined to be outstretched during task; **auditory stimuli continued during rest; #mean score on Handedness Scale (range 0–7). 7 completely right-handed.

Specific Motor Imagery Instructions, ie NOT to perform visual imagery or 3rd person imagery.

MRT indicates mental rotation task; EMG, electromyography; Obs, observation; N/A, not addressed; CMI, controllability of motor imagery.
TABLE 5. Functional Imaging Studies: Activation Patterns During the Motor Imagery Task vs Rest, Using Voxel-Based Whole-Brain Analysis

<table>
<thead>
<tr>
<th>Study</th>
<th>M1</th>
<th>SMA</th>
<th>Pre-SMA</th>
<th>Ba6</th>
<th>GPo</th>
<th>Ba</th>
<th>Sup.P</th>
<th>Ant.Cing</th>
<th>Inf.P</th>
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<tbody>
<tr>
<td>Binkofski (2000)</td>
<td>-</td>
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<td>Boecker (2001)</td>
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<td>Naito E (2002)</td>
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<td>Lacourse (2005)</td>
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M1 indicates primary motor cortex; SMA, supplementary motor cortex; Ba, brodmann area; Sup.P, superior parietal lobe; Inf.P, inferior parietal lobe; Gpo, post central gyrus; CB, cerebellar; Ant.Cing, anterior cingulate.

Table 5 summarizes cortical activation patterns in M1, the primary motor cortex, and other motor-related areas. Only 1 study documents M1 activation during motor imagery, which was bilateral and localized to the hand area; however, the activation was less than during executed movement. The use of random effect analysis on only 8 subjects, as performed in 1 study, is conservative and may have contributed to the failure to demonstrate M1 activation, particularly as thresholds varied; 2 studies used P<0.01 (corrected), and 193 P<0.001 (uncorrected).

Activation Patterns. When needed, the published activation coordinates were transformed into Talairach space using Mni2tal and then checked manually against the Talairach atlas. ROI Studies

General Features. The 6 relevant ROI-based studies are detailed in Table 6. The objective of the studies varied; 3 studies focussed primarily on aspects of the motor imagery network. The studies are similar with regards to subject demographics, except the inclusion of left-handed subjects by 2 studies. Across the studies, motor imagery ability was not assessed and 2 studies did not explicitly instruct subjects to perform motor imagery. During the training phase, different methods were used to detect overt movement: observation,95,97 goniometer,66 and EMG.99 In this particular study the subjects continued training until they subjectively scored >4 on a kinaesthetic scale with a silent EMG.

TABLE 6. ROI-Based Functional Imaging Studies*

<table>
<thead>
<tr>
<th>Author</th>
<th>Objective of Study</th>
<th>Subject No Gender and Handedness</th>
<th>(Paced)</th>
<th>ROI Used</th>
<th>Statistical Methods</th>
<th>PcG Activation During Motor Imagery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lotze (1999)</td>
<td>Cortical activation patterns particularly M1 and 2nd Motor Structures</td>
<td>10 (5 M, 10 RH)</td>
<td>Fisting (1 Hz)</td>
<td>Anatomical</td>
<td>Voxel based P&lt;0.01 (uncorrected)</td>
<td>Bilateral M1</td>
</tr>
<tr>
<td>Hanakawa (2003)</td>
<td>Cortical activation patterns Motor Imagery</td>
<td>10 (7 M, 10 RH)</td>
<td>Finger tapping (Non paced)</td>
<td>Functional ROI</td>
<td>Signal based in suprathreshold voxels P&lt;0.001</td>
<td>No M1 activation</td>
</tr>
<tr>
<td>Rodriguez (2004)</td>
<td>Role of M1 in different conditions</td>
<td>10 (7 M, 8 RH)</td>
<td>Finger tapping (phasic/tonic Motor Imagery)</td>
<td>(1.5 Hz)</td>
<td>Anatomical</td>
<td>Signal based P&lt;0.05</td>
</tr>
<tr>
<td>Solodkin (2004)</td>
<td>Network Modelling Motor Imagery</td>
<td>9 (18 in study) (9 M, 14 RH)</td>
<td>Finger tapping (2 Hz)</td>
<td>Anatomical</td>
<td>Signal based P&lt;0.05</td>
<td>Contra-lateral M1</td>
</tr>
<tr>
<td>Niyazov (2005)</td>
<td>Compare executed movement and Motor Imagery fMRI and TMS</td>
<td>6 (3 M, 6 RH)</td>
<td>Finger thumb Opposition</td>
<td>Self paced (1 Hz)</td>
<td>Anatomical</td>
<td>Voxel Based P&lt;0.01 (corrected)</td>
</tr>
<tr>
<td>Hanakawa (2005)</td>
<td>Ipsilateral precentral motor areas</td>
<td>8 (5 M, 8 RH)</td>
<td>Finger tapping</td>
<td>Anatomical</td>
<td>Voxel Based P&lt;0.001 (uncorrected)</td>
<td>Ipsilateral Pcm (PMd) only</td>
</tr>
</tbody>
</table>

Abbreviations: See previous tables. PMd indicates dorsal premotor; PcG, precentral gyrus.

*All of these studies used a box car design unless stated and rest as a contrast; † event-related design.
Motor Imagery Training

The findings of the 5 studies reviewed suggest that motor imagery training might have an encouraging effect on motor function after stroke. However, interpretation of these results is limited by small sample sizes and heterogeneity in subject characteristics, motor imagery interventions and outcome measures used. In addition it is likely that some subjects may have been performing chaotic motor imagery as a result of the lesions involving the motor imagery network, yet despite this they still managed to achieve a positive effect on functional performance. This does raise an interesting paradox: motor imagery training, which is less effective than physical practice in controls, may produce greater functional gains than executed movement in patients with stroke who can move, as claimed by Liu et al. This observation being isolated, however, it should be considered with caution. Furthermore, a possible explanation was alluded to by Crosbie et al, subjects often continue motor imagery training unsupervised, increasing the frequency of intervention. Alternatively, it is conceivable that patients performing chaotic motor imagery are more sensitive to and have the most to gain from training.

Clearly more research is needed in this area.

Although motor imagery training is theoretically independent of motor recovery, in the studies reviewed the control intervention required motor performance. In doing so, they excluded subjects with severe hemiparesis, who may have a different response to motor imagery training. For instance, an intriguing paradigm could be to use motor imagery at the stage of complete hand paresis so as to activate the motor network as a substitute to CIT, and to switch to modified CIT as soon as sufficient hand movement has returned.

Furthermore, the optimal period to start motor imagery training is unclear. Unlike AMT, motor imagery could potentially be started early after stroke when the brain may be most receptive to intervention, although it is becoming increasingly clear that active motor training may be effective even in the chronic stage of stroke. Nonetheless, whether motor imagery training is capable of producing long-term gains is unknown.

In summary, motor imagery training is a promising intervention to improve motor function after stroke, but adequately powered clinical trials are needed in groups of well-characterized, stroke subjects. Furthermore, adequate screening and monitoring tools should be used to ensure that subjects included in these trials are able to and do perform motor imagery. Finally, the most appropriate target population, ie, those with severe hemiparesis, have not been studied as yet.

Functional Imaging

The findings from the 5 main studies detailed here highlighted robust and consistent activation of the secondary motor network and ipsilateral cerebellum during motor imagery, but only weak or inconsistent M1 activation.

To what extent these results are affected by methodological pitfalls is unclear. None of the studies reviewed complied with all the quality controls discussed above (see also implications for future studies below). Across the studies, subject screening and monitoring during both the training and imaging paradigm varied markedly in its purpose, with no study adequately assessing all facets of noncompliance. Hanakawa et al was the closest to optimal by including monitoring of performance during scanning, yet even with the additional statistical powering
of ROI analysis found no M1 activation whatsoever in 9 of their 10 subjects. In contrast, Lacourse et al.\(^{104}\) used whole-brain analysis and documented strong bilateral M1 activation; however, some of their subjects were left-handed. Moreover, attributable to the lack of appropriate screening/monitoring, the validity of the results is uncertain.

Although the use of rest (with cues on) as a baseline condition provides an appropriate contrast and eases comparison between paradigms, it can be difficult to control.\(^{102}\) Nonetheless, motor imagery studies that use cognitive baseline conditions rather than rest, which are difficult to place in context, are also undecided about the role of M1. Using visual imagery as a baseline, Porro et al.\(^{110,111}\) and Kuhtz-Buschbeck et al.\(^{112}\) report M1 activation, although significantly less than during executed movement; conversely, Dechent et al.\(^{78}\) used the same paradigm but failed to show M1 activation, although suggested fleeting M1 activation on the initiation of motor imagery. Nonetheless, by contrasting body parts specific activation, Ehreson et al.\(^{118}\) have suggested that motor imagery engages somatotopically organized areas of the M1, as did also Stippich et al.\(^{116}\) Alternative methods of accessing the motor imagery network such as Luria hand rotation task\(^{57}\) activate secondary motor structures but not M1.

The repeated failure to consistently activate M1 in functional imaging studies when other investigative methods, such as magnetoencephalography (MEG),\(^{103,104}\) electroencephalogram (EEG),\(^{105,106}\) and TMS,\(^{107-110}\) are supportive of its involvement is puzzling. The higher spatial resolution of fMRI may be a contributing factor. However, it is plausible that during motor imagery, M1 has a different role beside executive, and so its activation is less sustained than during actual movement, producing a much-reduced signal. Importantly, in the primate, M1 is involved in spatial processing during motor imagery.\(^{18}\) In addition, M1 can participate in the processing of both serial order information\(^{111,112}\) and task-related spatial information,\(^{113}\) whereas in humans it can be modulated by attention\(^{114}\) and has the capacity to store short-term procedural information,\(^{115}\) implying motor imagery may involve generation of motor representations without movement.\(^{92}\)

Yet, despite differences in both subject selection and baseline tasks, the secondary motor structures, normally involved in motor learning, preparation, programming and memorizing,\(^{36}\) have consistently shown activation. Therefore, an alternative explanation for the weak and inconsistent M1 activation during motor imagery may be that the premotor areas inhibit an otherwise executive M1. In primates, premotor areas can modulate M1 in an inhibitory manner as well as excitatory.\(^{116}\) TMS studies in humans suggest that premotor-M1 interactions can also be inhibitory.\(^{117,118}\) Furthermore, connectivity analysis of fMRI data sets supports an inhibitory effect of supplementary motor cortex and superior parietal lobe on M1 during motor imagery.\(^{96}\) Although inhibition by secondary motor areas at the level of the anterior horn cell has been considered,\(^{96}\) this would be expected to be associated with high or even excessive M1 activation.

Because it is widely believed that effective training and rehabilitation methods after stroke should involve M1, does the apparently weak and inconsistent activation of M1 during motor imagery make it a doomed rehabilitative approach? Not necessarily so, for 3 distinct reasons. Firstly, this finding needs to be confirmed in methodologically flawless fMRI studies. Secondly, even a weak activation might be sufficient to prevent learned nonuse and “prime” the motor representations enough to result in minimal active movement, bridging the gap across to modified CFT.\(^{119}\) Thirdly, it remains possible that any effects of motor imagery are mediated by the premotor areas bypassing M1 via direct corticospinal projections, or improving preparation and programming rather than execution.\(^{28}\) Further speculation about the role of M1 and the secondary motor areas in healthy volunteers is difficult until the issues of subject selection and noncompliance have been dealt with.

The study of secondary dystonia does not clarify the involvement of M1; nonetheless, it highlights some of the difficulties in applying motor imagery to patients with stroke: (1) patients had parietal dysfunction and may have been performing chaotic motor imagery even though they still scored well on the MIQ; (2) the potential difficulties in interpreting cortical activation patterns when subject compliance cannot be objectively confirmed; and (3) dystonia after adult onset stroke is a very unusual condition whose relevance to stroke in general is uncertain.

An interesting parallel are motor imagery studies in patients with complete spinal cord injury (SCI), where the lesion resembles subcortical stroke to a greater extent. Functional imaging\(^{120,121}\) studies in SCI patients have reported marked M1 activation during motor imagery of the feet. Alkadhi et al.\(^{120}\) surprisingly reported a similar M1 cluster size in SCI patients as during executed movement in controls, who, notably, failed to activate M1 during motor imagery. This provides further support that the premotor areas may be inhibiting an otherwise executive M1 during motor imagery. Interestingly, healthy volunteers were screened with the MIQ, but SCI subjects were unable to perform the movements required by the MIQ, highlighting the need for alternative methods of assessment. It is possible, however, that motor imagery performed by SCI subjects differs in some fundamental aspects from that performed by healthy subjects.

### Implications for Study Design

#### Subject Selection

Based on the above review, subjects, particularly those with stroke, should have an objective assessment of their capacity to perform motor imagery and exclude chaotic motor imagery before inclusion into either motor imagery training or functional imaging studies. They should also be given clear instructions; these should include specifying 1st person motor imagery and advice against the use of alternative strategies such as counting or visual imagery. Attempts should be made to identify noncompliant subjects.

#### Motor Imagery Training

Because motor imagery is, in principle, independent of motor performance, it would seem prudent that the control intervention for future motor imagery training studies does not require motor performance. This will further characterize the effects of motor imagery training, as will monitoring for uncontrolled motor imagery training use. Pragmatically, monitoring
for noncompliance during motor imagery training is challenging; however, the use of mental chronometry\textsuperscript{28} is likely to be an effective means. Finally, further research should compare the effects of intervention in groups of low and high performers, to test the “bridging” hypothesis.

**Functional Imaging Paradigm Design**

Motor imagery may prove to be a consistent activation task that can be used across the full range of recovery and is largely independent of motor performance. The activation task should be simple and quick enough to be completed by patients with stroke while allowing objective evidence of compliance. To allow meaningful interpretation, particularly in subjects with stroke, the baseline condition should be rest (with cues).

**Conclusions**

The literature reviewed suggests that in healthy subjects motor imagery activates the motor network, providing a plausible mechanism for motor imagery training in athletes. No useful information is available as yet in patients with stroke, and the underlying mechanism of motor imagery training–induced improved performance suggested by the literature remains unexplained. However, if the same relationship as SCI patients is maintained in stroke, this may suggest that patients with chronic hemiplegia would involve M1 to a greater degree during motor imagery, providing a potential target group for motor imagery training.

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None.

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Motor Imagery. A Backdoor to the Motor System After Stroke?
Nikhil Sharma, Valerie M. Pomeroy and Jean-Claude Baron

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