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1 **Impact of neurologic deficits on motor imagery: A systematic review of clinical evaluations**

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10

11           **Abstract**

12           Motor imagery (MI, the mental representation of an action without engaging in its actual execution) is a  
13 therapeutically relevant technique to promote motor recovery after neurologic disorders. MI shares common  
14 neural and psychological bases with physical practice. Interestingly, both acute and progressive neurologic  
15 disorders impact brain motor networks, hence potentially eliciting changes in MI capacities. How experimental  
16 neuroscientists and medical practitioners should assess and take into account these changes in order to design  
17 fruitful interventions is largely unresolved. Understanding how the psychometric, behavioral and  
18 neurophysiological correlates of MI are impacted by neurologic diseases is required. To address this brain-  
19 behavior issue, we conducted a systematic review of MI data in stroke, Parkinson’s disease, spinal cord injury,  
20 and amputee participants. MI evaluation methods in clinical research are presented. Redundant MI profiles,  
21 primarily based on psychometric and behavioral evaluations, emerged in each clinical population. When present,  
22 changes in the psychometric and behavioral correlates of MI were highly congruent with the corresponding  
23 motor impairments. Neurophysiological recordings yielded specific changes in cerebral activations during MI,  
24 which mirrored structural and functional reorganizations due to neuroplasticity. In this view, MI capacities may  
25 not be deteriorated *per se* by neurologic diseases resulting in chronic motor incapacities, but adjusted to the  
26 current state of the motor system. Literature-driven orientations for future clinical research are provided.

27           **Keywords:** Motor imagery, Stroke, Parkinson’s disease, Spinal cord injury, Amputation, neuroplasticity.

## 28 1 Introduction

### 29 1.1 Motor imagery

30 Motor Imagery (MI) is the internal representation of an action without engaging its physical execution.  
31 Neuroimaging findings provided evidence that MI and physical practice (PP) were functionally equivalent, *i.e.*,  
32 recruit *overlapping* brain regions within the brain motor networks underlying motor preparation and execution,  
33 including pre-motor, parietal, primary somatosensory and motor cortices (for reviews, see Munzert and Zentgraf  
34 2009; Jeannerod 1994, 2001; Guillot et al. 2014; Munzert et al. 2009; Lotze and Halsband 2006; Guillot et al.  
35 2012a; Hetu et al. 2013; Holmes and Collins 2001). Cerebral networks controlling MI and PP of the same task  
36 are hierarchically organized, with higher recruitment of central and cerebellum motor regions during PP  
37 (Macuga and Frey 2012). Reduced activation intensities by 30 to 50 % are usually recorded during MI within the  
38 primary motor and somatosensory cortices (Lotze and Halsband 2006; Porro et al. 1996). Functional differences  
39 between MI and PP primarily account for the absence of overt motion and lack of movement-related sensory  
40 feedback under the MI condition. Brain motor system activation is stronger for MI modalities presenting a  
41 “*small subjective distance between the self and his own imaginal experience*” (Jeannerod 1995). Due to their  
42 embodied nature, first person (*i.e.*, ‘seen from inside’) and kinesthetic MI have greater functional equivalence  
43 with PP (Solodkin et al. 2004; Guillot et al. 2009; Lorey et al. 2009; Stinear et al. 2006; Lotze and Halsband  
44 2006). Likewise, MI expertise leads to more focused recruitment of the brain motor networks and higher  
45 activation intensities (Guillot et al. 2008; Lebon et al. 2012; Marks and Isaac 1995; van der Meulen et al. 2012;  
46 Williams et al. 2012; Lorey et al. 2011).

47 The involvement of a task-specific corticospinal network during MI is also largely documented (for  
48 review, see Stinear 2010). Typically, a transcranial magnetic stimulation (TMS) pulse is applied to the primary  
49 motor cortex as participants engage into MI (Fig. 2b). Pyramidal neurons are activated trans-synaptically through  
50 electromagnetic induction (Rothwell 1991), and the resulting motor evoked potential is recorded at the peripheral  
51 level using surface electromyography (EMG; Fig. 2b). Stimulation protocols, by varying the number, intensity  
52 and frequencies of magnetic pulses, allow specific investigations of intra-cortical facilitation or inhibition during  
53 mental and motor tasks (Reis et al. 2008; Dayan et al. 2013). Facilitation of the corticospinal tract during MI  
54 (*e.g.*, reduced motor threshold, decreased motor evoked potentials latencies and increased amplitude, or higher  
55 extension of the cortical sites of facilitation as compared to rest) is reduced compared to PP (Clark et al. 2004;

56 Leonard and Tremblay 2007), but is nonetheless specific according to the prime agonist muscles of the imagined  
57 task (Kasai et al. 1997; Facchini et al. 2002; Stinear and Byblow 2003; Rossini et al. 1999); similarly as during  
58 motor preparation (Tomberg and Caramia 1991). Furthermore, corticospinal facilitation is time-locked to the  
59 imagined phases of muscle activation (Fadiga et al. 1999; Levin et al. 2004). For instance, Stinear and Byblow  
60 (2003) reported facilitation of thumb abductor muscles only when participants imagined the contraction phase of  
61 the corresponding movement. Corticospinal facilitation during MI accounts for both increased intra-cortical  
62 facilitation and reduced intra-cortical inhibition (Stinear 2010; Takemi et al. 2013) and resembles that elicited by  
63 small muscle contractions (Abbruzzese et al. 1999). However, TMS studies provided inconclusive results as  
64 regards facilitation of spinal motoneurons during MI (Stinear 2010, for a specific discussion). This was typically  
65 addressed in TMS designs by recordings Hoffman's reflex as participants engaged during MI. EMG  
66 experiments, by contrast, provided evidence for facilitation of Hoffman's reflex during MI (Bonnet et al. 1997;  
67 Hale et al. 2003), thus supporting the possible recruitment of alpha motor neurons. Since the pioneering work by  
68 Jacobson (1930, 1932), subliminal muscle activations during MI were regularly reported, and the properties of  
69 the somatic signals resembled actual motor commands (Wehner et al. 1984). Muscles responses are further  
70 known to increase according to the physical effort required by the imagined action (Bakker et al. 1996; Boschker  
71 2001). While some authors challenged the hypothesis of muscle responses during MI, or their specificity (e.g.,  
72 Shaw 1938), Gandevia et al. (1997) argued on the basis of microneurographic recordings that during MI trials  
73 eliciting sufficiently strong neuromuscular activity, sensory feedback from spindles were also present, thus  
74 describing a subliminal feedback loop of motor control which could reinforce motor programs (*i.e.*, the psycho-  
75 neuromuscular theory of motor learning). Recently, Guillot et al. (2007) observed that muscles responses during  
76 MI mirrored the contraction type, and preserved both muscles synergies and agonist/antagonist patterns of  
77 coordination (see Fadiga et al. 1998; Tamaki et al. 2013 for analogous conclusions on the basis of TMS  
78 findings).

79 Overall, a strong neuroscientific background supports the central elaboration of motor command signals  
80 during MI (Guillot et al. 2012a). However, the neural commands for muscular contractions are blocked at some  
81 level of the motor system by active inhibitory mechanisms (Jeannerod 1994; Berthoz 1996; Lotze et al. 1999;  
82 Guillot et al. 2012a). MI can thus be considered a "*special form of motor behavior*", intermediate in the  
83 continuum extending from motor preparation to motor execution (Stephan et al. 1995; Stephan and Frackowiak  
84 1996; Nikulin et al. 2008; Stinear 2010).

85 1.2 *Mental practice*

86 “In contrast to the imagery process *per se*, mental practice (...) consists of a training method by which  
87 the internal reproduction of a given motor act is repeated extensively with the intention of improving  
88 performance”, Jackson et al. (2001), p. 1133.

89 Since Warner and McNeill (1988), theoretical rationale supporting the use of mental practice (MP; *i.e.*,  
90 as described in Jackson et al. 2001; see above) in neurologic rehabilitation benefited from neuroimaging  
91 evidence for functional equivalence between MI and PP (*e.g.*, Munzert et al. 2009; Mulder 2007; Jackson et al.  
92 2001; Decety 1993). MP might, like PP training, induce activity-dependant neuroplasticity (*i.e.*, the capacity of  
93 the neural tissue to reorganize its anatomical and functional synaptic properties). Brain imaging studies in  
94 healthy participants (HPs) disclosed MP-dependant neuroplasticity yielding to motor performance improvements  
95 (Jackson et al. 2003; Pascual-Leone et al. 1995; Lacourse et al. 2004; Zhang et al. 2012; Zhang et al. 2011;  
96 Nyberg et al. 2006; Ranganathan et al. 2004). It is however well-admitted that MP benefits do not outperform  
97 those elicited by PP. Their combination yielded stronger improvements in motor learning and rehabilitation  
98 (Feltz and Landers 1983; Driskell et al. 1994; Guillot and Collet 2008; Jackson et al. 2001).

99 “If you cannot perform an action physically, you cannot imagine it in a way that is necessary for a high  
100 degree of functional equivalence”.

101 This theoretical postulate by Olsson and Nyberg (2010; p. 711) challenges the therapeutic rationale of  
102 MP programs in neurologic rehabilitation. Previous reviews explored the best rules for MI practice in medicine  
103 and disciplines related to motor performance (*e.g.*, Schuster et al. 2011; Braun et al. 2008; Braun et al. 2013), or  
104 discussed how a specific component of MI accuracy could be altered by neurologic diseases (*e.g.*, Malouin and  
105 Richards 2010; Sharma et al. 2006; Munzert et al. 2009; Guillot et al. 2012b). Nonetheless, to the best of our  
106 knowledge, a systematic review of MI evaluation methods and data from clinical experiments is lacking. MI  
107 evaluation in healthy individuals ideally requires combining tools from different scientific fields, namely *i*)  
108 psychometric tests, *ii*) behavioral tests using mental chronometry and *iii*) neurophysiological measures of central  
109 and peripheral nervous system activities (Collet et al. 2011; Guillot and Collet 2005b). Accurate MI performance  
110 is expected to elicit similar psychometric, behavioral and neurophysiological correlates as PP of same task (for  
111 reviews, see Annett 1995; Collet et al. 2011; Holmes and Collins 2001; Guillot and Collet 2005b). We sought to  
112 provide such analysis on the basis of experimental data in stroke (STR), Parkinson’s disease (PKD), spinal cord

113 injury (SCI) and amputated (AMP) participants. In a first part, we introduce descriptive data related to the  
 114 literature database search. We then discuss the specificities of MI evaluation techniques used in clinical settings  
 115 while the third part is designed to provide a review of MI data yielded in clinical populations. On this basis,  
 116 literature-driven orientations for future research are finally considered.

## 117 2 Literature review

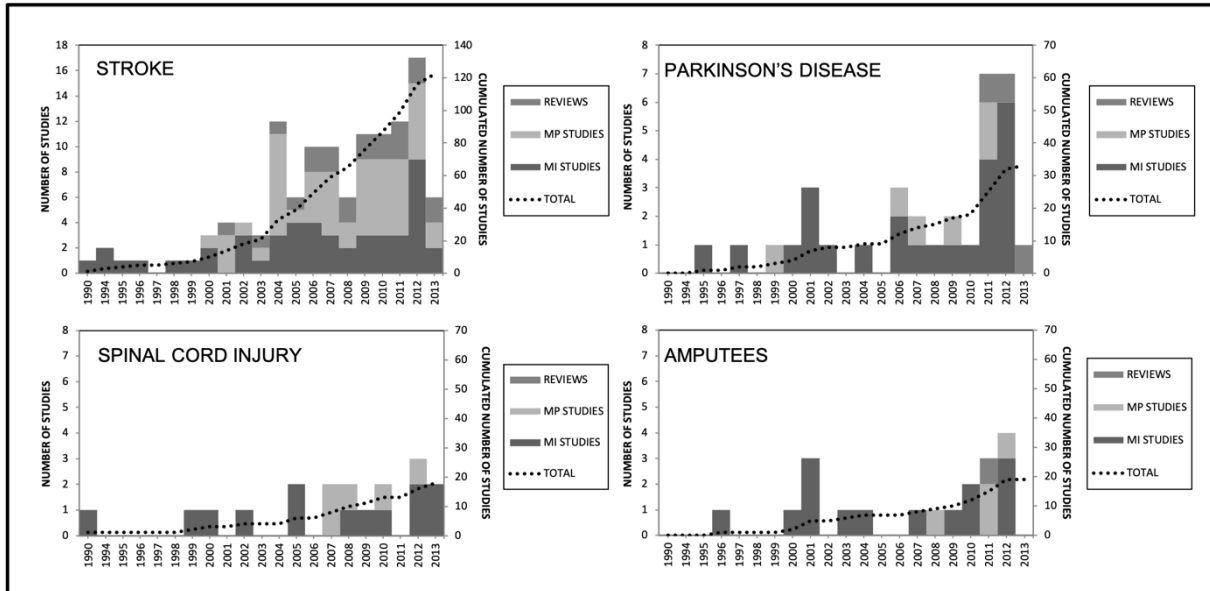
118 Biomedical studies were selected from the MEDLINE®/PubMed® database up to August 2013. Were  
 119 included: *i)* MP studies (*i.e.*, *longitudinal* studies testing MP efficacy in clinical rehabilitation settings), and *ii)*  
 120 MI studies (*i.e.*, transversal MI studies reporting MI data on the basis of psychometric, behavioral and  
 121 neurophysiological evaluations). Were excluded: *i)* brain-computer interfaces studies with a primary  
 122 methodological focus, *ii)* experiments including participants with various pathologies within the same  
 123 experimental group, and *iii)* review articles discussing MI issues in several clinical populations, which could thus  
 124 not be categorized as belonging to the field of STR, SCI, PKD and AMP research. A large sample of 192  
 125 references meeting the inclusion criteria emerged (Table 1), using the search terms “Motor imagery”,  
 126 “Movement Imagery”, “Imagery”, “Imagination”, “Mental practice” “Mental training” and “Motor imagery  
 127 training” in combination with “stroke”, “Parkinson”, “Amputee”, “Amputation”, “spinal cord injury” using the  
 128 “AND” Boolean operator.

	MI studies	MP studies	Reviews	Total
STR	49	52	21	122
PKD	24	6	3	33
SCI	13	5	0	18
AMP	14	4	1	19
Total	98	67	25	192

129

130 **Table 1.** Number of Motor Imagery intervention and assessment studies in stroke (STR), spinal cord  
 131 injury (SCI), Parkinson’s disease (PKD) and amputees (AMP) participants from 1990 up to August 2013. The  
 132 highest publication rate was for STR studies (64 %).

133 In the STR group, we collected a similar number of MI and MP studies (Table 1), and detected an initial  
 134 burst of publications in 2004 (Fig. 1). In PKD, SCI and AMP populations only few MP studies were found [*i.e.*,  
 135 range = 4 - 6, representing 19 % (PKD), 29 % (SCI), and 22 % (AMP) of MP studies].



136  
 137 **Fig. 1.** MI, MP studies and reviews published per year in stroke, spinal cord injury, Parkinson's disease and  
 138 amputee participants (source: MEDLINE®/PubMed®). The TOTAL dotted line is to be referred to on the right  
 139 axis. For purposes of graphical display, the y-axis scale was half-reduced for studies in Parkinson's disease,  
 140 spinal cord injury and amputee participants. MI: Motor Imagery, MP: Mental Practice

141 *2.1 Motor imagery studies*

142 42 % of MI studies (range = 35 – 50 % across clinical populations) conducted psychometric  
 143 evaluations, 35 % (range = 10 to 41 % across clinical populations) conducted behavioral evaluations, and 57%  
 144 (range = 38 % to 90 %) conducted neurophysiological recordings. 40 % (range = 38 to 62 % across clinical  
 145 populations) used more than one assessment method. We identified two different types of designs. In 85 % of the  
 146 experiments, the participants were *explicitly* instructed to engage into MI (*n.b.*, most experiments involved first-  
 147 person visual MI, sometimes combined with kinesthetic information). In another 15 %, they were requested to  
 148 solve a cognitive task *implicitly* requiring MI, but were not instructed to engage into MI. In 86 % of these  
 149 implicit MI studies, participants were requested to *determine laterality* of some body parts as fast and accurately  
 150 as possible. Other implicit MI paradigms required *determining feasibility* or limb posture during virtual grasping  
 151 of visually presented tri-dimensional objects (*e.g.*, Frak et al. 2004; Johnson 2000; Johnson et al. 2002). In the

152 following sections, we will basically refer to “MI” and “implicit MI” when required. Implicit MI tests are  
153 objective and reproducible, but do not control individual cognitive strategies used to solve the task (section  
154 7.2.1.2).

155         Explicit and implicit MI experiments both afford standardized evaluations, but relate differently to  
156 motor cognition. Explicit MI is a “*dynamic state during which the representation of a given motor act is*  
157 *internally rehearsed without motor output*” (Decety and Grezes 1999). MI thus involves motor simulation, *i.e.*,  
158 predictive models derived from the efferent copy of the motor command (Grush 2004; Wolpert and Flanagan  
159 2001; Demougeot and Papaxanthis 2011; Wolpert and Ghahramani 2000). Conversely, implicit MI can be  
160 regarded as a “*prospective action judgment*” or a “*perceptually induced motor decision*” (Johnson et al. 2002;  
161 Jeannerod 2001), and primarily address participant’s capacities to engage into projection and manipulation of  
162 their body schema (Parsons 1987a, 1987b).

## 163 2.2 *Mental practice studies*

164         MP studies primarily investigated efficacy of the technique on motor disabilities (88 %). Reviewing  
165 efficacy of MI training is not the purpose of the present work, as this issue has already been extensively  
166 considered in recent review papers (see Schuster et al. 2011 for recent reviews; Faralli et al. 2013; Bowering et  
167 al. 2013; Malouin et al. 2013). Inclusion of MP experiments in this systematic review was nonetheless necessary  
168 to understand how MI was evaluated in clinical research protocols. Such evaluations have two purposes: *i)*  
169 determining participant’s capability to engage into MP (*preliminary* MI evaluation), and *ii)* determining MI  
170 quality during MP interventions (*control* of MI training).

171         Previous research yielded that only 11 MP medical studies out of 37 included MI assessments (Schuster  
172 et al. 2012c; Schuster et al. 2011). In the present literature review, 48 % of MP studies included preliminary MI  
173 assessments. Psychometric assessment methods were by far the most frequently encountered (96 %), followed  
174 by behavioral and neurophysiological methods (respectively, 36 % and 3 %). Only 19 % used more than one  
175 assessment method. Present data corroborate Schuster et al. (2011)’s conclusions concerning limited attention  
176 paid to preliminary MI evaluation. Description of the methods used to control MP lacked in 43 % of studies. MP  
177 was mainly controlled by means of psychological and behavioral tests (79 % and 24 %, respectively).

178

### 179 3 Motor imagery evaluation methods in clinical experiments

180 Clinical evaluations, practical aspects related to their clinical use, and components of MI quality being  
181 measured are summarized in Table 3 (p. 23).

#### 182 3.1 Psychological methods

183 Oral debriefs, MI questionnaires and self-report ratings are reliable psychometric methods to evaluate  
184 MI quality in HPs (Guillot and Collet 2005b). Tests which we will refer to as “*congruency tests*” were also found  
185 in clinical studies (see below).

##### 186 3.1.1 Explicit motor imagery

187 Oral debriefs were primarily used to control adherence to MI instructions during *preliminary*  
188 assessments (e.g., Kuhn et al. 2006). Oral debriefs also served to control MP (e.g., Dijkerman et al. 2004;  
189 Simmons et al. 2008). Generally speaking, use oral debriefs is mentioned but detailed report of its content  
190 lacking. The interview procedures were almost never detailed. To date, only one study reported detailed MI  
191 content, use and experience along the course of MP on the basis of oral debriefs (Schuster et al. 2012b).

192 Standardized questionnaires evaluating MI “*ividness*” and “*ease*” were widely used in MI and MP  
193 designs (respectively 38 % and 21 % of studies). Most MI vividness questionnaires used in neurologic  
194 populations were developed and validated in HPs (the Vividness of Visual Imagery Questionnaire, VVIQ; Marks  
195 1973; e.g., the Vividness Movement Imagery Questionnaire, VMIQ; Isaac et al. 1986; and its revised version,  
196 VMIQ-2; Roberts et al. 2008; the Questionnaire upon mental imagery, QMI; Sheehan 1967). Vividness  
197 questionnaires required participants to perform MI of several standardized motor tasks, sometimes preceded by  
198 their physical execution. Participants then provided a vividness score on a 5 or 7-level Likert scale, typically  
199 ranging from *no image at all / vague perception* up to *identical sensory experience as PP*. Ease questionnaires  
200 measured the experienced difficulty at performing MI, again using Likert-type scales ranging from *very easy* to  
201 *very difficult* (e.g., the Movement Imagery Questionnaire, MIQ; Hall and Martin 1997; and its two revised  
202 versions, MIQ-R and MIQ-RS; Hall and Pongrac 1983; Gregg et al. 2010). Some ‘ease’ questionnaires designed  
203 for HPs were also shown reliable for assessments in clinical populations (e.g., the MIQ-RS; Butler et al. 2012).  
204 However, questionnaires items frequently involved movements which were not targeted by the rehabilitative  
205 intervention, or single-joint movements that were not goal-directed. Such tasks are in opposition with the task

206 used in MP designs (*i.e.*, MI of goal-directed actions involving affected body parts). Questionnaires items also  
207 involved motor tasks entirely decoupled from clinical participant's current motor capabilities (*e.g.*, "*Jumping*  
208 *straight in the air*"). In some clinical interventions, experimenters relevantly adapted questionnaires' content to  
209 participant's motor repertoire, for instance by removing items that persons could no longer perform (*e.g.*,  
210 Dickstein et al. 2004; Diers et al. 2010; Welfringer et al. 2011). To date, the only questionnaire designed to  
211 assess MI in participants with motor impairments, and used to assess vividness in each of our populations of  
212 interest, is the Kinesthetic and Visual Imagery Questionnaire (KVIQ; Malouin et al. 2007). A recent  
213 questionnaire was also developed for assessment of gait MI vividness after PKD, albeit data revealed limited  
214 sensitivity to gait-related disorders (Pickett et al. 2012). Importantly, MI ease and vividness can be collected by  
215 means of self-reports using Likert-type or visual analogous scales (*e.g.*, Gustin et al. 2010; Lotze et al. 2001;  
216 Moseley 2007). Compared to standardized questionnaires, these can be collected from *any* MI task, and  
217 represent user-friendly techniques in clinical settings. MI questionnaires enable standardized assessments and  
218 provide a *general* psychometric index. Yet, these remain highly subjective methods. Schuster et al. (2012c)  
219 validated in STR and PKD subjects the translation of the Imagix software (Fournier 2000) which allows more  
220 objective assessments of MI vividness and modality. Ultimately, logbooks enable collection of most  
221 psychometric MI data (vividness, ease and accuracy) and can be used to control unsupervised MP (*e.g.*, Jackson  
222 et al. 2004; Dijkerman et al. 2004; Gaggioli et al. 2009; Braun et al. 2011; Braun et al. 2010).

223 Psychometric evaluations also included "*congruency*" tests (*e.g.*, Samuel et al. 2001; Li 2000; Hotz-  
224 Boendermaker et al. 2008; Sharma et al. 2009a; Sharma et al. 2009b; de Vries et al. 2011; Braun et al. 2011;  
225 Szameitat et al. 2012). Congruency tests address the *accuracy* of MI (*i.e.*, exactness of MI content). Participants  
226 are first requested to perform MI of a sequential motor task (*i.e.*, involving various sets of movements, or  
227 cyclical repetitions of the same action). They are then interrupted at some point of the process controlled by the  
228 experimenter. Finally participants must verbally describe the MI content at the point of interruption. MI accuracy  
229 can also be evaluated *after* completion of the imagined actions. For instance, participants chose among various  
230 pictures representing different body positions which corresponds to the body position achieved through MI (*e.g.*,  
231 Li 2000; de Vries et al. 2011), or described orally the final imagined body position. The "*Questionnaire of*  
232 *mental imagery: rotation of hands*" (Sirigu and Duhamel 2001) is a congruency test which was used to  
233 investigate accuracy of MI content in STR participants with and without visual neglect (Vromen et al. 2011).  
234 Congruency tests also enabled to *control* of MP (*e.g.*, Kim et al. 2011; Muller et al. 2007).

235 3.1.2 *Implicit motor imagery*

236 *Psychometric* implicit MI assessments focused on *accuracy*. In mental rotation of body parts paradigms  
237 (*e.g.*, recognition of laterality), accuracy referred to the number of correct answers over the total number of  
238 presented stimuli (Nico et al. 2004; Helmich et al. 2007; Fiori et al. 2013; Yan et al. 2012). In implicit MI tasks  
239 involving determination of action feasibility, or body postures compatibility during hand-objects interactions,  
240 accuracy referred to congruency between participants' "*prospective action judgments*" and the *actual* feasibility  
241 / compatibility (*e.g.*, Johnson et al. 2002; Johnson 2000; Frak et al. 2004; Buxbaum et al. 2005).

242 3.2 *Behavioral methods*

243 3.2.1 *Explicit motor imagery*

244 Mental chronometry affords investigation of the time course of information processing by the CNS  
245 (Posner 1978). As MI implies absence of overt motion, a relevant 'behavioral' evaluation method consists in  
246 recording the duration of MI (Collet et al. 2011; Malouin et al. 2008b). The ability to achieve tight temporal  
247 correspondences between MI and PP time is a reliable marker of MI accuracy (for a recent review, see Guillot et  
248 al. 2012b). Mental chronometry tests allowed both *preliminary* MI assessments (Malouin et al. 2009b; Simmons  
249 et al. 2008; Sharma et al. 2009a; Sharma et al. 2009b) and *control* of MI training (*e.g.*, Malouin et al. 2004c;  
250 Dunskey et al. 2006; Dunskey et al. 2008; Braun et al. 2011). Behavioral methods represent an objective approach  
251 to the issue of MI evaluation in clinical populations, but do not provide any qualitative information about MI  
252 content *proper*.

253 Correspondence between MI and PP times is often referred to as "*temporal equivalence*" in the  
254 scientific literature. However, temporal equivalence *indiscriminately* referred across experiments to *i*)  
255 statistically significant correlations between MI and PP durations (*i.e.*, "temporal congruence"), or *ii*) absence of  
256 statistically significant differences between mean/median MI and PP durations (*i.e.*, "isochrony"). Temporal  
257 congruence and isochrony are however *distinct* components of MI accuracy. In the perspective of using mental  
258 chronometry in clinical research, this point must be clarified. The statement of "*temporal equivalence*" should  
259 ideally refer to presence of *both* temporal congruence (*i.e.*, correlation between MI and PP durations) and  
260 isochrony (*i.e.*, absence of difference between MI and PP durations). If MI and PP involve common motor  
261 planning strategies, the time necessary to complete the two tasks should be close (Decety and Michel 1989;  
262 Decety et al. 1989). Factors affecting PP duration (*e.g.*, task complexity) should elicit a parallel increase in MI

263 durations. Therefore, PP and *accurate* MI times should be correlated. By contrast, uncorrelated MI and PP  
264 durations unambiguously reflect MI deficits (e.g., Sirigu et al. 1996; Danckert et al. 2002). Temporal congruence  
265 thus implies that factors impacting PP timing yield to *parallel* changes on MI timing. The effects of task  
266 complexity (e.g., Sirigu et al. 1996; Danckert et al. 2002), task duration (e.g., Malouin et al. 2008b, 2008a), limb  
267 dominance (e.g., Decety and Boisson 1990; Dominey et al. 1995), and laterality of the motor deficits (i.e., task  
268 actual duration performed with spared or impaired peripheral effectors; e.g., Decety and Boisson 1990; Sirigu et  
269 al. 1995; Sirigu et al. 1996; Raffin et al. 2012a) were thus tested in clinical evaluations. Isochrony, similarly as  
270 temporal congruence, reflects the recruitment of predictive models for actual actions during MI (Guillot et al.  
271 2012b; Papaxanthis et al. 2002). While absence of isochrony can be due to MI deficits (e.g., inconsistencies  
272 between motor predictions and actual motor capabilities), it may also result from factors *external* to the subject.  
273 For instance, movements longer than 30 s tend to be underestimated, whereas the opposite is observed for  
274 complex or short-lasting motor sequences (Guillot et al. 2012b). Contrary to temporal congruence, the  
275 relationship between isochrony and MI ability is not straightforward. MI and PP durations can be highly  
276 *correlated*, yet with persistent *overestimation or underestimation* of PP durations due to task specificities.

277           Standardized chronometric tests generally involved motor sequences ranging from 5 to 30 s (Table 2).  
278 When a short motor task (i.e., inferior to 3 or 5 s) was used, it was being repeated several times in order to make  
279 the resulting duration compatible with reliable chronometric measurements (e.g., stepping actions; Malouin et al.  
280 2008b, 2008a). Some tests did not record MI durations *per se*, but the number of motor sequences mentally  
281 completed within a predetermined time period (e.g., Stinear et al. 2007; Malouin et al. 2009b, 2008b, 2008a).  
282 Experimenters checked presence of a linear increase in the number of repetitions according to increasing time  
283 periods allocated to MI (i.e., an index of temporal congruence). Experimenters also checked that the number of  
284 imagined movements was similar to the number of movements physically performed within an identical time  
285 period (i.e., an index of isochrony). Some behavioral MI assessments *did not involve* recordings of PP durations.  
286 Such behavioral methods appeared of specific interest to limit interferences between PP and MI processes in  
287 people with motor incapacities (Table 2). Raffin et al. (2012a) tested the effect of body posture on MI durations  
288 in AMP subjects. Participants were requested to imagine a pointing action, with their arm being alternatively in a  
289 physically compatible or incompatible position for physical execution of the task. Congruent body position was  
290 expected to exert a priming effect on MI, which should be facilitated in the case of compatible body position  
291 (i.e., hence elicit shorter durations compared MI performed with the arm being in an incompatible body position;

292 Sirigu and Duhamel 2001). This test allowed objective assessment temporal congruence in spite of missing limb  
293 due to AMP.

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Behavioral MI tests in MI studies with STR, PKD, SCI and AMP participants

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Reference	Name	Task	Behavioral outcome	Goal-directed	Duration
[1]	NA	PP and MI of a set of functional tasks: signing, drawing, hopping	Isochrony, and higher durations expected during PP and MI with the non-dominant limbs	Y	≈ 5 - 30 s
[2 – 7]	Break test	PP and MI of a finger-to-thumb opposition sequence in response to a metronome. Speed of the metronome increased every five seconds	Congruence between PP and MI break points ( <i>i.e.</i> , point to which subjects could no longer follow the metronome)	N	NA
[2], see [8] for adapted version	NA	PP and MI of sequential finger movements of varying complexity	Temporal congruence according to the complexity of the finger sequence, and isochrony	N	≈ 5 - 30 s
[1-2, 9]	NA	PP and MI of a manual pointing task with a stylus, from a standardized starting position to a variable-size opened square drawn on a paper sheet	Temporal congruence according to the perceptual demand of the motor task	Y	5 – 15 s
[10]	NA	PP and MI of a sequential task involving moving a joystick in different directions	Isochrony	Y	≈ 5 s
[11]	NA	PP and MI of arm pointing task: pointing five times at two targets within arm reach placed on both sides of a table in front of the subject	Isochrony	Y	≈ 2 s
[11]	NA	Actual and imagined performance of leg stepping task: moving one foot 5 times forward onto a block (target) and then moving it backward to the starting position	Isochrony	N	≈ 2 s

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[17]	NA	Actual and imagined pointing at different body regions starting from the nose ( <i>i.e.</i> , navel, contralateral shoulder, ipsilateral shoulder, and then back to the nose)	Isochrony estimated by the number of PP and MI repetitions completed during 30 s	N	NA
[12 -18]	NA	Actual and imagined performance of uni- and bimanual finger opposition sequences	Temporal congruence according to task complexity	N	≈ 10 - 25 s
[19 - 20]	Time-Dependant Motor Imagery Test (TDMI)	Actual and imagined stepping movements from a sitting position: then, placing one foot forward onto a board (target) and returning to the floor	Temporal congruence estimated by the number of PP and MI repetitions during trials according to sequence duration ( <i>i.e.</i> , 15, 25, 45s or 35s; presented in a pseudo-randomized order)	N	NA
[20, 22]	Temporal congruence test	Similar movements to the TDMI test, executed by sequences of five	Isochrony through calculation of the ratio between PP and MI durations	N	≈ 10 s
[22]	NA	Set of activities of daily living: reaching and grasping a cup, turning a page of a book, using a hairbrush/comb, proper use of writing and eating utensils	Isochrony	Y	≈ 5 – 15 s
[23]	NA	PP and MI of walking along a path of varying distance towards a door of fixed or varying width	Isochrony and temporal congruence according to the effect of path distance and door width	Y	≈ 2 – 5 s
[6 – 7, 24]	Mental version of the box and blocks test	Box and blocks test: moving a defined number of cubes ( <i>i.e.</i> , fifteen or twenty) of small size from one box to the other	Isochrony, correlations between PP and MI durations at the group level were reported in Heremans et al. (2012)	Y	≈ 15 – 30 s

[25]	NA	Finger movements of varying complexity imagined five times with right and left upper limb using of kinesthetic MI, PP of the same tasks with the unaffected limb	Temporal congruence according to task complexity for right and left upper limb	N	≈ 5 – 30 s
[26]	NA	MI of walking along a path of varying distance and width	Congruence of MI durations according to path distance and width	Y	≈ 5 – 15 s
[18]	Visuomotor incongruency test [30]	MI of touching the mouth with the hand and returning back to a standardized starting position with the arm being alternatively in a congruent or incongruent posture for PP of the task	Temporal congruence according to compatibility of current body position with respect to MI content ( <i>i.e.</i> , slower times expected when arm posture incompatible with MI content)	N	≈ 5 – 10 s

**Table 2.** Behavioral tests found in MI studies<sup>1</sup>. Behavioral MI tests used in MP studies are not reported. These tests are redundant with those of MI studies or involve standardized functional tasks analogous to those used for MI training. MI = Motor Imagery, PP = Physical Practice, NA = Not Available. References index: 1 = Decety and Boisson (1990); 2 = Sirigu et al. (1995); 3 = Sirigu et al. (1996); 4 = Sharma et al. (2009a); 5 = Sharma et al. (2009b); 6 = Heremans et al. (2011); 7 = Heremans et al. (2012); 8 = Schwoebel et al. (2002); 9 = Danckert et al. (2002); 10 = Thobois et al. (2000); 11 = Malouin et al. (2004b); 12 = Dominey et al. (1995); 13 = Thobois et al. (2002); 14 = Sabate et al. (2004); 15 = Gonzalez et al. (2005); 16 = Sabate et al. (2007); 17 = Stinear et al. (2007); 18 = Raffin et al. (2012a); 19 = Malouin et al. (2008a); 20 = Malouin et al. (2008b); 21 = Malouin et al. (2012); 22 = Wu et al. (2010); 23 = Cohen et al. (2011); 24 = Dettmers et al. (2012); 25 = Szameitat et al. (2012); 26 = Snijders et al. (2011); 27 = Sirigu and Duhamel (2001).

<sup>1</sup> Please note: reliability of the timed-up and go test for behavioral MI assessment was also demonstrated (Malouin et al., 2010) albeit this reference was not available from the MEDLINE®/PubMed® literature database search (section 2).

Behavioral MI tests involved both goal-oriented movements with a clear functional purpose and single-joint movements decoupled from the environmental context (Table 2). In the latter case, motor tasks are easier to control and reproduce. Motor tasks for behavioral MI tests can be adapted to suit participant's current motor capabilities (e.g., Malouin et al. 2008b). Behavioral assessments may involve cueing conditions. For instance, Sirigu et al. (1996) used a metronome and participants indicated at which point they could no longer follow its pace during actual and imagined finger tapping (Table 2). Dunskey et al. (2006) controlled accuracy of MP using a metronome: its cadence was set up to the natural gait cadence of STR participants. After initiation of imagined gait, beats were interrupted, and participants were requested to announce completion of six additional mental steps. This approach afforded control of MP timing, and can be viewed as a 'behavioral' MI congruency test. Some authors suggested that MI should be performed before PP during behavioral tests, in order to prevent the use of alternative cognitive strategies such as counting (e.g., Sharma et al. 2009a; Sharma et al. 2009b; Malouin et al. 2008b). Others instructed to perform PP before MI of the task (Stinear et al. 2007; Wu et al. 2010).

### 3.2.2 *Implicit motor imagery*

*Behavioral* implicit MI assessments investigated participants' reaction times (RTs); *i.e.*, considered the time elapsed between presentation of the to-be-rotated stimulus and participant's answer, which includes the reaction time *proper* and the movement time required to trigger an answer command<sup>2</sup>. RTs increase proportionally with the distance separating stimulus orientation from the actual body position, thus supporting that participants imagine their own body parts moving towards the stimulus (Parsons 1987a, 1987b, 1994). The effect of actual body posture (*i.e.*, longer RTs expected when the body is in an incompatible position; Nico et al. 2004; van Nuenen et al. 2012), motor impairment (*i.e.*, different RTs expected if the to-be-rotated stimuli involves affected or unaffected body parts; Helmich et al. 2007), and dominance side (*i.e.*, longer RTs expected for recognition of laterality of stimuli corresponding to the non-dominant side; Dominey et al. 1995; Nico et al. 2004) on RTs was used in clinical studies. Implicit MI designs may involve the presentation of *two* identical visual stimuli with different spatial orientations. Participants were then requested to identify whether the two

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<sup>2</sup> Participants with motor deficits are usually requested to press an answer command with lesser or unaffected body parts, or on the basis eye movements, so as to prevent a confounding effect of motor deficits on RTs.

stimuli were identical (*e.g.*, whether the two hands are of identical laterality). RTs increased proportionally with the degree of mental rotation needed for their alignment. With reference to Shepard and Cooper (1986) the slope coefficient of the regression function between RTs and degrees of mental rotation required to solve the implicit MI task provides the RT / degree, *i.e.*, an index of mental rotation processes. The y-intercept of the regression function reflects cognitive processes distinct from mental rotation proper, for instance spatial encoding or preparation of the behavioral response (*e.g.*, Amick et al. 2006 for an illustration). Implicit MI assessments did usually not require PP of the task, excepted when congruency between “*prospective action judgments*” and PP was evaluated (*e.g.*, Buxbaum et al. 2005).

### 3.3 *Neurophysiological methods*

Neurophysiological methods involve recordings of both central and peripheral nervous system activities during MI (Collet et al. 2011; Guillot and Collet 2005b). Neurophysiological evaluations mainly consisted in CNS recordings using brain imaging [magnetoencephalography, functional magnetic resonance imaging (fMRI), and positron emission tomography; see Fig. 2c for classic scanning designs] or TMS techniques (representing respectively 74 % and 20 % of MI studies involving neurophysiological measurements). Investigation of the neurophysiological correlates of MI in STR, SCI, PKD and AMP people were reported in 60 % of MI studies. These were however rarely used in MP designs (see section 2.2), presumably due to medical, material and temporal constraints. Neurophysiological recordings are objective, but difficult to relate to the psychometric and chronometric indexes of MI quality (Table 3). Further research in this direction is required (section 6.3). Nonetheless, neurophysiological methods enable direct investigation of the functional equivalence between MI and PP, and determine whether the cerebral substrates underlying MI (or implicit MI) are comparable in clinical populations and HPs. They have thus powerful implications concerning the possibility of using MI to induce MP-dependant neuroplasticity.

#### 3.3.1 *Central nervous system recordings*

MI and implicit MI experiments both involved CNS recordings (*i.e.*, representing 68 % and 33 % of MI studies, respectively). Due to methodological limitations (*e.g.*, the need to keep the head motionless during scanning), simple motor tasks without functional purpose usually supported CNS recordings (*e.g.*, 65 % of brain imaging MI studies). MI tasks nonetheless involved body limbs targeted by rehabilitative intervention (*e.g.*,

actions with the affected upper or lower limbs, respectively for the purposes of prehension and gait rehabilitation).

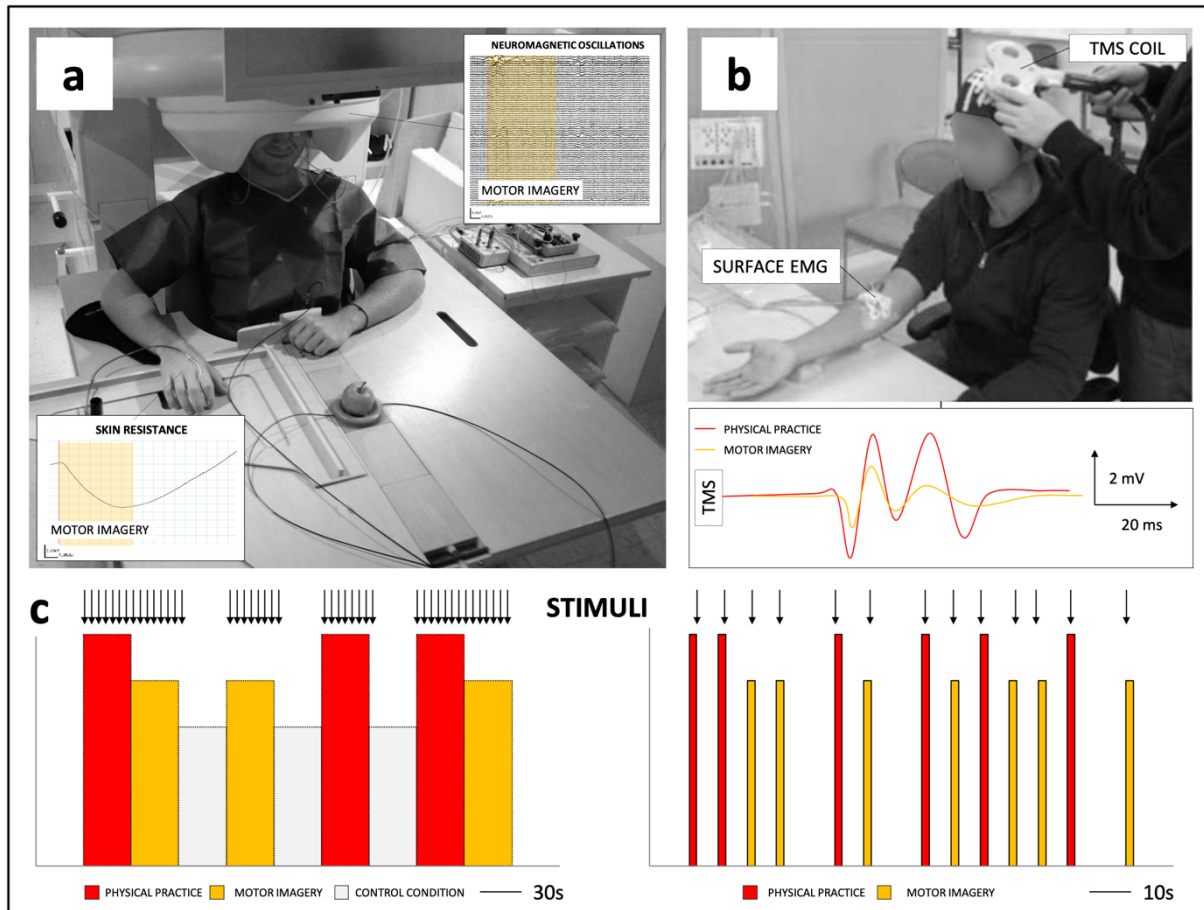
### 3.3.2 *Peripheral recordings*

Somatic and autonomic responses can be recorded at the peripheral level of the motor system due to selective and incomplete inhibition of motor command signals during MI (Collet and Guillot 2009).

No relationship between EMG activity and the components of MI quality emerged in HPs (Guillot and Collet 2005b; Guillot et al. 2010). In STR participants, Dickstein et al. (2005) found no correlation between subliminal EMG activity during MI and MIQ scores. By contrast, Heremans et al. (2008) provided evidence that recording eye movements during MI with electro-oculography enabled objective assessment of MI quality. Particularly, task-related eye movements were reproduced during accurate MI of visuo-motor tasks (i.e., a tight correspondence in the number and amplitude of eye movements was recorded; Heremans et al. 2008). However, the relevance of electro-oculography recordings for assessment of MI quality of tasks with a poor visuo-motor component may be more limited.

Autonomic nervous system responses (e.g., cardiorespiratory and electrodermal activities) are usually elicited as early as participants engage into MI, and enable objective evaluations of MI quality (Collet et al. 2013; for a review). Only reports of electrodermal recordings were found in reviewed experiments (section 4.3.1). Electrodermal activity reflects the activity of eccrine sweat glands. These are under the unique control of the sympathetic branch of the autonomic nervous system (Shields et al. 1987) and can be recorded from various neurologically healthy body regions (e.g. hand palm, neck; Matsunaga et al. 1998; Yildiz et al. 2007). Electrodermal responses are characterized by sudden baseline drops in skin resistance, immediately followed by a slower and regular return to baseline (Fig. 2a). *Phasic* activity reflects mobilization of mental resources during MI, particularly vigilance and attention. In this view, recording *phasic* activity during MI of complex and goal-directed tasks is of primary interest. Electrodermal responses duration were correlated to MI vividness in HPs (Guillot and Collet 2005b; Di Rienzo et al. 2012). Interestingly, the *tonic* level can be used as an index of mental fatigue and physiological arousal during MP sessions (Collet et al. 2011). Skin resistance should return to basal levels after MI trials, without progressive increase towards higher basal values in the case of sustained sympathetic activity throughout the session (Collet et al. 2011). Decay in task novelty, for instance repeated MI of the same action, might result in increased tonic level and decreased sudomotor responses amplitude and

duration. Monitoring electroencephalographic activity could also be a direct approach to this issue (e.g., Rushby et al. 2013 for an illustration of combined electroencephalographic and skin resistance recordings in subjects with brain injuries).



**Fig 2.** Illustration of neurophysiological methods to assess MI. **a.** Experimental settings combining central (Magnetoencephalography, CTF-MEG system - 275 Channels, CERMEP - Imagerie du vivant) and peripheral electrophysiological recordings (Electrodermal recordings using two 30 mm<sup>2</sup> unpolarizable Ag/AgCl electrodes placed on the second phalanx of the second and third fingers of the non-dominant hand; Clark Electromedical Instruments, Ref. E243) during MI of a prehensile task. **b.** Figure-of-eight coil used for transcranial magnetic stimulation of the contralateral primary motor cortex during MI of forearm movements (used with permission from Professor Kuniyasu Imanaka). Motor potentials evoked by transcranial magnetic stimulation, usually compound potentials of three or four ‘indirect’ waves, are recorded in the prime movers of the imagined action by surface electromyography. They are of reduced magnitude compared to PP. **c.** Schematic representation of a block-design (left side) and an event-related design (right side) that can be used in MI paradigms. Most reviewed MI experiments implemented block designs. In the block design, several trials (black arrows) are performed

successively during periods of 20-30 s for each condition. Before block onset, instructions are provided to participants during brief periods (2-10 s). Brief 'rest' periods distinct from control condition can also be included to prevent from physical/mental fatigue in clinical populations. In the event-related design, each experimental condition is presented at random (vertical bars and arrows). MI: Motor Imagery, TMS: Transcranial Magnetic Stimulation, EMG: electromyography

Evaluation method		Psychometric			Behavioral		Neurophysiological			
Evaluation techniques		Oral debriefs	Standardized questionnaires	Congruency tests	Likert ratings	Mental chronometry	Peripheral recordings		CNS recordings	
							Neurovegetative activity	Electro-oculography	TMS	Brain imaging
Data type	Subjective (self-report)	+	+		+					
	Objective (measure)			+		+	+	+	+	+
Main purpose	Preliminary assessment	+	+	+	+	+	+	+	+	+
	Control of training	+		+	+	+	+	+		
MI recording	Before						+			
	During			+		+	+	+	+	+
	After	+	+	+	+		+			
Practical characteristics	Ambulatory/semi-ambulatory	+	+	+	+	+	+	+		
	Not ambulatory									+
	Standardized assessment		+	+	+	+		+		
	Adaptable to clinical tasks	+		+	+	+	+		+	+
	Require physical practice of the task		+	+	+	+	+	+	+	+
MI quality	Perspective	+	+		+					
	Vividness	+	+		+		+			
	Ease	+	+		+					
	Accuracy	+	+	+	+					
	Temporal congruence					+		+ <sup>†</sup>		
	Isochrony					+		+ <sup>†</sup>		

**Table 3.** MI evaluation methods available from clinical experiments. All methods enabled *preliminary* MI assessments. Methods allowing *control* of training with MI are indicated. Most psychometric methods can be combined to behavioral and neurophysiological evaluations. Strong complementarities emerged across evaluation methods in the perspective of clinical assessments. \*Variable across tests. <sup>†</sup> Electrodermal responses duration can be correlated or compared to actual task durations in order to provide information concerning MI timing.

## 4 Motor imagery correlates in clinical populations

In this section, we seek to delineate the psychometric, behavioral and neurophysiological correlates of MI after STR, SCI, PKD and AMP. MI and implicit MI results are discussed separately. We dissociated MI changes which were specific to a given state of neurologic impairment (*i.e.*, severity, nature, stage of the pathology) from *redundant* changes in MI capacities across experiments reflecting the impact of the disease on MI quality (*i.e.*, neurologic MI profiles).

### 4.1 Psychological correlates

#### 4.1.1 Explicit motor imagery

A first category of experiments yielded high MI vividness scores in the clinical populations of interest (e.g., Malouin et al. 2004c; Malouin et al. 2004a; Dickstein et al. 2004; Jackson et al. 2004; Dickstein et al. 2005; Grangeon et al. 2012b; Malouin et al. 2009b; Alkadhi et al. 2005; Heremans et al. 2011; Lotze et al. 2001; Hovington and Brouwer 2010; Raffin et al. 2012a; Butler et al. 2012; Schuster et al. 2012a; Peterson et al. 2012). Neurologic participants achieved vivid visual or kinesthetic MI, similarly as HPs, and reported identical MI ease on the basis of Likert self-reports (Stinear et al. 2007; Cramer et al. 2005; Tremblay et al. 2008; Marconi et al. 2007; Sharma et al. 2009a). Congruency tests evidenced preserved MI accuracy in STR, PKD and SCI people (Sharma et al. 2009a; Sharma et al. 2009b; Hotz-Boendermaker et al. 2008; de Vries et al. 2011; Samuel et al. 2001). We did not find reports of psychometric MI congruency tests in AMP subjects.

In a second category of experiments, psychometric evaluations also yielded *selective MI deficits* corresponding to the actual clinical impairments, particularly in STR, PKD and AMP participants with lateralized motor incapacities. Malouin et al. (2009a) described reduced MI *vividness* in AMP participants for KVIQ tasks involving the missing limb. Vividness scores resembled those obtained in a group of HPs who underwent limb immobilization. Malouin et al. (2009a) further reported that onset of walking with prosthesis correlated with increased KVIQ scores on the amputated side. These findings confirmed previous observations by Nico et al. (2004), and presumed integration of prosthesis with a natural functionality to the body schema (*i.e.*, by opposition to purely esthetic limb prosthesis). Lower MI vividness for impaired limbs was also observed in STR participants with lateralized motor impairments (Dettmers et al. 2012; Malouin et al. 2008a). In PKD subjects, Heremans et al. (2011) did not observe asymmetrical MI vividness KVIQ scores. By contrast, Randhawa et al. (2010) observed higher variability of KVIQ scores during axial movements (*i.e.*, head and trunk

movements in the sagittal plane). The authors stated that “*difficulty in axial imagery may be a result of changes in muscles that accompany PKD*”. Authors thus related MI vividness changes to PKD-related motor deficits. In the studies by Szameitat et al. (2012) and Raffin et al. (2012a), STR and AMP participants experienced lower MI *ease* for actions involving impaired / missing limbs. Li (2000) finally observed reduced MI *accuracy* when the task involved impaired limbs in cortical and putamen STR participants. Contrary to other populations, the psychometric correlates of MI appeared unaffected in SCI subjects (Grangeon et al. 2012b; Alkadhi et al. 2005; Hotz-Boendermaker et al. 2008). It was recently advanced, that SCI subjects might benefit from other sensory input than proprioception (*e.g.*, visual input through observation) to maintain and update motor representations (Di Rienzo et al. 2013).

#### 4.1.2 *Implicit motor imagery*

Implicit MI *accuracy* was reported intact in some experiments including STR, PKD and AMP subjects (Johnson 2000; Johnson et al. 2002; Buxbaum et al. 2005; van Nuinen et al. 2012; Heremans et al. 2011; Helmich et al. 2007; Curtze et al. 2010).

*Selective* MI accuracy deficits corresponding to actual motor impairments were also reported among the same populations of interest, particularly in persons presenting lateralized motor symptoms. For instance, STR and PKD subjects showed reduced MI accuracy for recognition of limbs corresponding to the damaged side (Dominey et al. 1995; Daprati et al. 2010). STR subjects with visual neglect exhibited MI deficits restricted to the neglected side (Coslett 1998); albeit Vromen et al. (2011) did not replicate this finding.

In specific cases, reduced implicit MI accuracy were detected *regardless* the actual motor deficits (Johnson et al. 2002; Schwoebel et al. 2002; Fiori et al. 2013; Tomasino et al. 2003; Frak et al. 2004; Yan et al. 2012; Vromen et al. 2011; Nico et al. 2004). Frak et al. (2004) reported, in PKD participants, an impaired capacity to predict feasibility of sizing actions which could still be performed physically. Amick et al. (2006) observed that implicit MI accuracy was impaired in hemi-PKD participants according to the visual field of stimulus presentations. The authors argued for differential involvement of the fronto-parietal networks underlying mental rotation, causing impairment of mental rotation processes in left, but not in right hemisphere PKD. Nico et al. (2004) observed that AMP participants who lost their non-dominant limb had identical implicit MI accuracy scores as HPs, whereas those who lost their dominant limb presented overall reduced implicit MI accuracy. Fiori et al. (2013) recently showed that SCI participants with complete motor deficits presented higher

implicit MI accuracy than HPs. Particularly, they did not present a burst in error rate when to-be-rotated stimuli were displayed in difficult orientations. This pattern of results was present for MR of both hands and letters and the authors concluded that complete deafferentation and deafferentation led, due to reduced capabilities to interact with the environment, to the emergence of cognitive strategies based on semantic knowledge and memory that replaced reference to the body schema.

#### 4.1.3 Motor imagery profiles based on psychometric data

Briefly speaking, psychometric evaluations yielded three redundant MI data profiles. Intact MI capacities (*i.e.*, high performance or identical results as in HC; 46 % of MI studies with psychometric data), or selective deficits according to the current motor incapacities. These two neurologic MI profiles represent 93 % of pooled psychometric data in STR, SCI, PKD and AMP participants (Table 4). MI and implicit MI deficits reflect actual motor impairment in 65 % of cases. Finally, for implicit MI only, deficits *irrespective* of the actual motor deficit were reported in STR, PKD and AMP (*i.e.*, 23 % of studies).

MI studies					
Neurologic MI profiles					
Number / Total of studies	STR	SCI	PKD	AMP	Total
Percentage					
1. High MI performance or equivalent to HPs	12 / 22 55 %	4 / 5	10 / 12 83 %	5 / 6 83 %	31 / 45 77 %
2. Selective MI deficits corresponding to the actual motor deficits	10 / 22 45 %	1 / 5	4 / 12 33 %	1 / 6 16 %	16 / 34 23 %
Implicit MI studies					
Neurologic MI profiles					
	STR	SCI	PKD	AMP	Total
1. MI capacities equivalent to HPs	8 / 12 66 %	0 / 1	4 / 8 50 %	2 / 2	13 / 20 65 %
2. Selective MI deficits according to the actual motor deficit	5 / 12 42 %	0 / 1	1 / 8 12 %	0 / 2	6 / 20 30 %
3. Impaired MI regardless the actual motor deficit	3 / 12 25 %	1 / 1	4 / 8 50 %	1 / 2	7 / 20 35 %

Table 4. Psychometric MI profiles in STR, SCI, PKD and AMP subjects based on MI studies. MI = Motor Imagery, STR = Stroke, SCI = Spinal Cord Injury, AMP = Amputee. Please note: percentages were not provided when there were 5 studies or less available in the category.

## 4.2 Behavioral correlates

### 4.2.1 Explicit and implicit motor imagery

Temporal equivalence referred the literature to temporal congruence, isochrony, or both (see section 3.1.1). In reviewed experiments, we noted a huge variability in chronometric data interpretation, particularly concerning isochrony. Importantly, HPs failed in some studies to achieve isochrony, particularly during MI of complex hand motor sequences requiring a high degree of accuracy (*e.g.*, Sabate et al. 2004, 2007; Stinear et al. 2007; Raffin et al. 2012a). Accordingly, mental chronometry assessments in HPs are crucial for interpretation of chronometric MI data in clinical populations.

A first class of chronometric evaluations yielded *identical* MI and implicit MI capacities in clinical populations and HPs (*e.g.*, Johnson 2000; Johnson et al. 2002; Malouin et al. 2008b; Heremans et al. 2011; Grangeon et al. 2012b; Decety and Boisson 1990; Di Rienzo et al. 2013; Raffin et al. 2012a; Helmich et al. 2011; Curtze et al. 2010). Behavioral MI tests which did not involve PP of the task (see Table 2) disclosed preserved MI timing congruency in STR, AMP and PKD subjects (Snijders et al. 2011; Malouin et al. 2008b; Raffin et al. 2012a). Importantly, two patterns of chronometric data support preserved MI timing accuracy: *i*) identical behavioral MI and implicit MI correlates to those recorded in HPs (Johnson 2000; Johnson et al. 2002; Malouin et al. 2009b; Thobois et al. 2002; Grangeon et al. 2012b; Di Rienzo et al. 2013), and *ii*) temporal congruence / isochrony between MI and PP with parallel increases durations due to the presence of motor deficits (Sirigu et al. 1995; Thobois et al. 2000; Gonzalez et al. 2005; Sabate et al. 2004, 2007; Decety and Boisson 1990; Heremans et al. 2012; Heremans et al. 2011; Malouin et al. 2009a; Thobois et al. 2002; Dominey

et al. 1995)<sup>3</sup>. Interestingly, this neurologic MI profile was early formalized in a pioneering review by Jeannerod (2001).

Other mental chronometry experiments evidenced MI deficits (*i.e.*, absence of temporal congruence and / or isochrony compared to MI of healthy body parts or MI of the same action in HPs) restricted to MI of affected limbs after AMP, STR and PKD (e.g., Sirigu et al. 1996; Dominey et al. 1995; Sabate et al. 2004; Daprati et al. 2010; Wu et al. 2010; Dettmers et al. 2012; Liepert et al. 2012; Raffin et al. 2012a)<sup>4</sup>. For instance, AMP participants showed similar patterns of temporal correspondences as HPs during MI of the unaffected limb but exhibited overestimation of PP durations when imagining the same action with the amputated limb (Raffin et al. 2012a).

Chronometric data finally revealed MI deficits *unrelated* to motor incapacities, particularly after STR and PKD (Sirigu et al. 1996; Danckert et al. 2002; Sabate et al. 2004; Frak et al. 2004; Malouin et al. 2004b; Yan et al. 2012). Overall, such MI deficits reflected the effect of the neurologic disorder on higher cognitive processes. For instance, a link between bilateral slowing of MI times and working memory impairments after STR was reported (Malouin et al. 2004b; Malouin et al. 2012). Working memory is involved in generation, maintenance and controllability of motor images (Malouin et al. 2004b; Malouin et al. 2012). Implicit MI paradigms also yielded *non motor-related* MI impairments. Yan et al. (2012) reported that deficient spatial encoding and spatial information processing, due to impaired neural processing within the visuo-motor network, elicited longer RTs in STR compared to HPs irrespectively of the hand (*i.e.*, affected or unaffected) involved. Frak et al. (2004) evidenced that bilateral idiopathic PKD subjects did not show RTs changes exhibited by HPs while determining feasibility of sizing an object according to different orientations (*i.e.*, shorter responses when stimuli were presented in preferred orientations). Finally, Nico et al. (2004) observed delayed RTs, during complex implicit MI tasks in subjects amputated from their dominant upper limb (*i.e.*, determining laterality of

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<sup>3</sup> See data in PKD participants in Sabate et al. (2004), data in AMP participants in Malouin et al. (2009), and data in STR participants in Decety and Boisson (1990)

<sup>4</sup> See data in participants with a right hemisphere STR in Sabate et al. (2004), data from the implicit MI task in Dominey et al. (1995).

hands in difficult orientations). Again, these were irrespective of the actual motor deficit and suggest preferential use of the dominant limb when reference to the body schema was required.

#### 4.2.2 Motor imagery profiles based on behavioral data

Four neurologic MI data profiles emerged from behavioral tests (Table 5): *i*) identical behavioral correlated as in HPs (*i.e.*, 27 % of MI studies), *ii*) preserved temporal coupling between MI and PP durations, yet with *parallel* increases in tasks duration compared to HPs due to the presence of a motor deficit (*i.e.*, 54 %), *iii*) temporal uncoupling between MI and PP durations, or delayed RTs during implicit MI, restricted to MI involving impaired limbs (*i.e.*, 43 %) and *iv*) MI (or implicit MI) impairments *irrespective* of clinical deficits (*i.e.*, 19 %).

MI studies					
Neurologic MI profiles Number / Total of studies Percentage	STR	SCI	PKD	AMP	Total
1. Temporal coupling patterns between MI and PP similar as in and HPs	6 / 20 12 %	2 / 2	1 / 8 14 %	1 / 2	10 / 32 31 %
2. Temporal coupling between MI and PP preserved and reflecting the motor deficits	9 / 20 47 %	0 / 2	6 / 8 71 %	1 / 2	15 / 32 47 %
3. Temporal coupling between MI and PP impaired according to the motor deficits	7 / 20 29 %	0 / 2	1 / 8 13 %	1 / 2	9 / 32 28 %
4. Temporal uncoupling between MI and PP irrespective of the actual motor deficit	8 / 20 35 %	0 / 2	0 / 8	0 / 2	25 / 32 35 %
Implicit MI studies					
MI Profiles	STR	SCI	PKD	AMP	Total
1. Similar RTs during implicit MI as in HPs	2 / 5 40 %	NA	3 / 8 38 %	2 / 2	6 / 14 42 %

2. Longer RTs compared to HPs only during implicit MI of affected body parts	2 / 5 40 %	NA	4 / 8 50 %	0 / 1	6 / 14 42 %
3. Longer RTs compared to HPs during implicit MI, irrespective of the actual motor deficit	2 / 5 40 %	NA	1 / 8 13 %	1 / 2	3 / 14 21 %

Table 5. Behavioral MI profiles in STR, SCI, PKD and AMP subjects, from MI studies. MI = Motor Imagery, STR = Stroke, SCI = Spinal Cord Injury, AMP = Amputee, NA = Not Available. Please note that percentages were not provided when less than 5 studies were available in the category.

### 4.3 Neurophysiological correlates

#### 4.3.1 Peripheral somatic and neurovegetative recordings

Peripheral somatic and neurovegetative recordings were rarely used in MI and MP studies (13 % and 3 %, respectively).

EMG recordings were primarily used to ensure that MI was completed without any concomitant muscle activity, but not to evaluate MI capacities *per se* (e.g., Cunnington et al. 1997; Kuhn et al. 2006; Heremans et al. 2012). EMG recordings were shown reliable to differentiate MI from attempted PP with the amputated limb (Raffin et al. 2012b; Raffin et al. 2012a). Efficacy of MP controlled with EMG neurofeedback finally provided mixed results in STR rehabilitation (Hemmen and Seelen 2007; Hwang et al. 2010). Generally speaking, the ability to engage the somatic motor system into the production of muscle responses is altered in persons suffering from *direct* CNS damage (i.e., STR, SCI and PKD participants), and may not be related to MI abilities (section 3.3.2). By contrast, Heremans et al. (2012) observed that oculomotor activity elicited during MI enabled reliable assessment of MI quality in PKD.

Electrodermal recordings were encountered in three experiments, and obtained by placing the electrodes on body regions with spared autonomic pathways in SCI participants (Grangeon et al. 2012a; Grangeon et al. 2012b; Di Rienzo et al. 2013). Sympathetic responses duration during MI were similar to those elicited during PP, which provided objective information concerning MI quality during preliminary assessments (Grangeon et al. 2012a; Di Rienzo et al. 2013). Grangeon et al. (2012a) reported that the level of injury and autonomic

dysreflexia history negatively correlated with electrodermal responses amplitude. Further reports of the autonomic nervous system correlates of MI in clinical MI research should be encouraged, because the lack of available data at this point prevents from drawing any definitive conclusions concerning their possible use and relevance for *clinical* evaluations of MI quality.

#### 4.3.2 Central nervous system recordings

##### 4.3.2.1 Transcranial magnetic stimulation data

TMS findings in STR and PKD participants support that corticospinal facilitation during MI of affected body parts is diminished within the clinically affected cerebral hemisphere (Battaglia et al. 2006; Filippi et al. 2001; Tremblay et al. 2008), but otherwise intact (Filippi et al. 2001; Battaglia et al. 2006). Nonetheless, STR participants further support preserved capacities to elicit an effector-specific pattern of corticospinal facilitation (Cincotta et al. 1999; Cicinelli et al. 2006; Battaglia et al. 2006). MI may thus be efficient to stimulate the corticomotor pathways and promote motor recovery (Cicinelli et al. 2006). This perspective was challenged by other TMS findings, particularly in STR participants with right hemisphere damage (Stinear et al. 2007). Participants failed to elicit corticospinal facilitation during MI of upper limb actions involving both the STR-affected and STR-unaffected sides, thus pointing out the specific role of the right hemisphere on “*higher order aspects of movement planning*” (Stinear et al. 2007). In the same vein, Liepert et al. (2012) reported that STR persons with severe somatosensory deficits had reduced corticospinal facilitation during MI of affected body parts as compared to STR participants without somatosensory deficits (*i.e.*, “*pure motor*” STR) and HPs. The data provided evidence of the specific role of somatosensory inputs in shaping the behavioral and CNS correlates of MI. In PKD participants tested “off” medication, corticospinal facilitation of affected body parts was absent during MI, a finding interpreted in terms of PKD effect on brain motor functions (Filippi et al. 2001; Tremblay et al. 2008). In AMP participants, corticospinal facilitation during MI evidenced weakened inhibitory interactions between foot and hand motor cortices, and thus mirrored sensorimotor neuroplasticity (Marconi et al. 2007). Obviously, corticospinal facilitation was absent during MI of infra-lesional actions in SCI participants (Cramer et al. 2007). Taken together, TMS data in STR, PKD and AMP people highlight selective effects of neurological impairments on primary sensorimotor recruitment during MI. Impaired facilitation seems restricted to the clinically affected hemisphere in lateralized STR and PKD participants (*i.e.*, weaker, lower or no facilitation observed as compared to HPs; or reduced facilitation compared to that elicited within the healthy cerebral

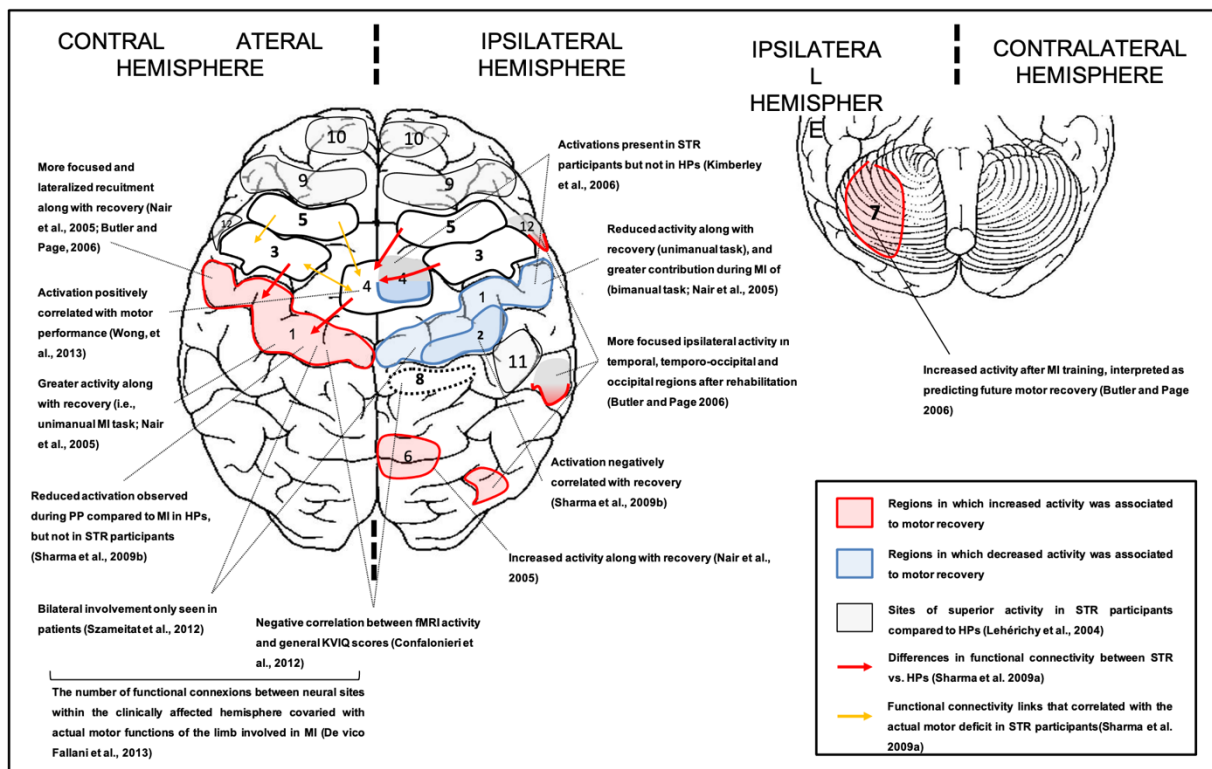
hemisphere). This neurologic MI profile corroborates psychometric and behavioral observations (see sections 4.1.3, 4.2.1). Analysis of whole brain imaging data is needed to understand MI changes in clinical populations.

#### 4.3.2.2 *Brain imaging*

##### 4.3.2.2.1 *Explicit motor imagery*

This section focuses on brain activity during MI of *impaired* movements. The neural networks of MI in clinical populations systematically differed from those in HPs'. Overall, brain activity mirrored neurologic impairments and adaptive neuroplasticity (Fig. 3 - 7; Sharma et al. 2009a; Sharma et al. 2009b; Cramer et al. 2005; Alkadhi et al. 2005; Hotz-Boendermaker et al. 2008; Thobois et al. 2000; Thobois et al. 2002; Snijders et al. 2011; Lotze et al. 2001; MacIver et al. 2008).

Brain imaging data provided evidence for preserved functional equivalence after STR. Nair et al. (2005) reported that cerebral activity reflected compensatory neuroplasticity related to the motor deficit after STR (*i.e.*, MI recruited similar networks as PP of actions with impaired limbs). MI also mirrored neuroplasticity associated with motor recovery (see Fig. 3; see also Kimberley et al. 2006; Butler and Page 2006; Sharma et al. 2009a; Sharma et al. 2009b; Szameitat et al. 2012). Recruitment of cortical resources within the unaffected cerebral hemisphere unveiled a STR-related compensatory network (Fig. 3; Kimberley et al. 2006; Sharma et al. 2009b; De Vico Fallani et al. 2013). Recruitment of sensorimotor and pre-motor regions within the unaffected hemisphere correlated with the clinical deficit (Sharma et al. 2009a; Sharma et al. 2009b). Conversely, increased recruitment of the precuneus and cerebellum, and focused recruitment of temporal and occipital regions within the unaffected hemisphere, reflected functional recovery (see Fig. 3; Nair et al. 2005; Butler and Page 2006). MI finally revealed brain motor system reorganizations which were not detectable during PP (*e.g.*, Sharma et al. 2009a; Sharma et al. 2009b; Kimberley et al. 2006). Sharma et al. (2009a) observed an analogous pattern of activations during MI of affected limb in STR and HPs. However, between-group differences emerged in functional connectivity between frontal and pre-motor regions (Fig. 3). Page et al. (2009) provided fMRI evidence that MP promoted contralateral and ipsilateral sensorimotor reorganizations, with enhanced beneficial effects on motor recovery [*e.g.*, increased scores on functional arm tests (Fulg-Meyer assessment and Action Research Arm test)] compared to PP training alone (see also results by Sun et al. 2013).

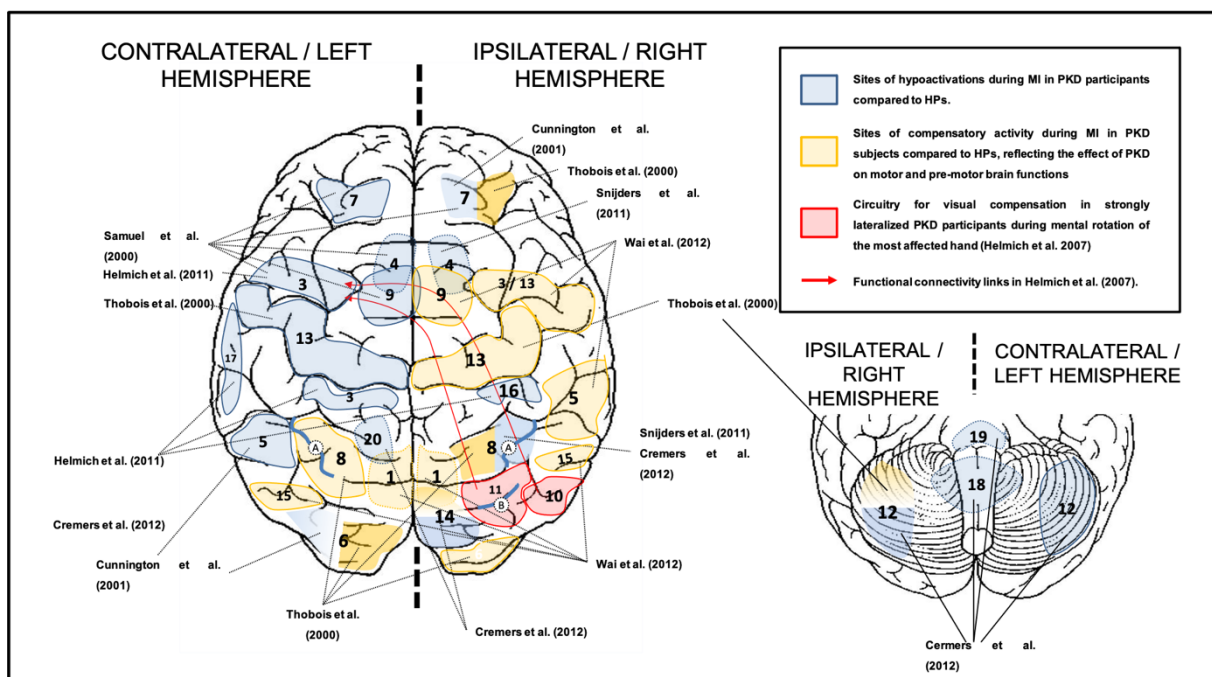


**Fig. 3.** Brain activity during MI of actions with STR-affected body parts reflecting neuroplasticity / motor recovery after stroke. Information is based on the results of brain imaging MI studies. 1: Primary motor cortex, 2: Posterior subdivision of primary motor cortex, 3: Pre-motor cortex, 4: Supplementary motor area, 5: Pre-frontal cortex, 6: Precuneus, 7: Cerebellar hemisphere, 8: Anterior subdivision of primary somatosensory cortex, 9: Frontal cortex, 10: Orbitofrontal cortex, 11: Inferior parietal lobe, 12: Anterior temporal lobe extending to insula on the ipsilateral side. Anatomical location of brain regions may be approximate for purposes of visual display. Dotted lines delineate subcortical structures. PP: Physical Practice, MI: Motor Imagery, STR: Stroke, HPs: Healthy Participants

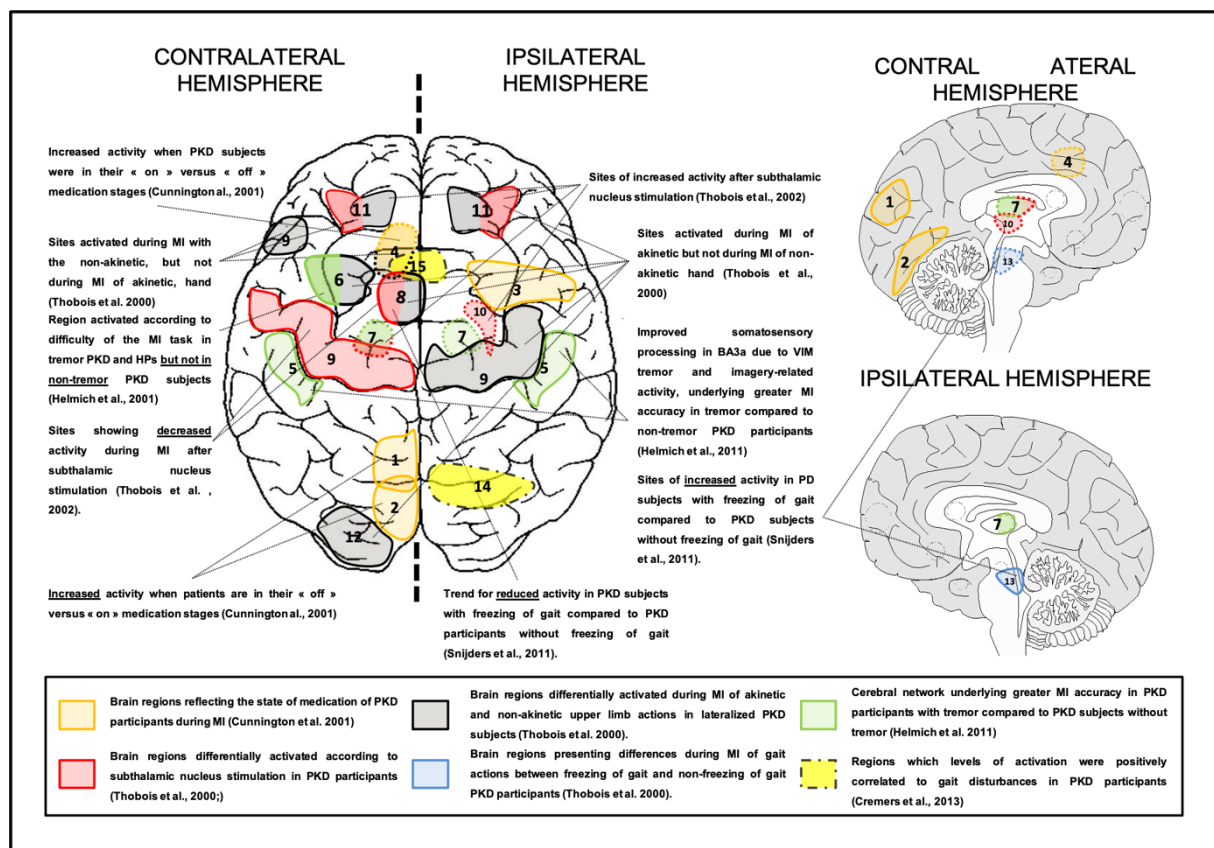
After hemi-PKD (*i.e.*, lateralized PKD-related motor symptoms), reduced activities were observed within the prefrontal, pre-motor, sensorimotor and parietal cortices of the clinically affected hemisphere (Cunnington et al. 1997; Thobois et al. 2000; Samuel et al. 2001). Changes were also reported at the subcortical level, with decreased activity in the ipsilateral cerebellum and cingulate areas (Thobois et al. 2000; Samuel et al. 2001). Hypo-activations were assumed to reflect deficits in motor preparation (Thobois et al. 2000; Samuel et al. 2001; Cunnington et al. 2001; Cunnington et al. 1997). In parallel, compensatory brain activations were observed in ipsilateral pre-motor, central and parietal regions compared to HPs (Fig. 4; Cunnington et al. 1997; Thobois et al. 2000; Samuel et al. 2001). Brain imaging thus revealed a pattern of inter-hemispheric compensation,

presumably resulting from adaptive neuroplasticity. Other brain imaging data provided evidence for increased dependence on visual information during both MI and implicit MI performance, mediated by pre-motor and occipital regions (Fig. 4 - 5; Helmich et al. 2007; van Nuenen et al. 2012; Wai et al. 2012).

Specific cerebral patterns of activity characterized PKD-related motor symptoms, such as tremor, freezing of gait or the absence of medication (Fig. 5). Reduced cingulate cortex, parietal and supplementary motor area activity during MI of walking reflected difficulties in establishing somatosensory and motor predictions in freezing of gait (Snijders et al. 2011; Poliakoff 2013). These data corroborate behavioral observations by Cohen et al. (2011). Experimental results support preserved functional equivalence after PKD, but patterns of cerebral activity differed from HPs due to the effect of disease on brain motor functions (Fig. 4; for a discursive review, see; Poliakoff 2013). Functional equivalence between MI and PP seems preserved after PKD. MI thus allows the study of brain motor functions after PKD (Maillet et al. 2012). Subramanian et al. (2011) evidenced that fMRI neurofeedback enabled PKD subjects to voluntarily recruit the supplementary motor area – with similar intensities as during PP. Clinically meaningful motor improvements (*i.e.*, increased movement speed on a finger-tapping test and reduced Unified Parkinson’s Disease Rating Scale scores) were observed after several weeks of home-based MP. These effects were not achieved by PKD participants who practiced MP without neurofeedback. The data confirm that functional equivalence with PP is a key factor underlying MP efficacy in rehabilitation.



**Fig. 4.** Brain activity during MI of PKD-affected actions reflecting hypo- and compensatory activations. Information is based on the results of brain imaging MI studies. 1: Precuneus, 2: Lingual Gyrus, 3: Pre-motor cortex, 4: Anterior Cingulate cortex, 5: Inferior parietal Lobule, 6: Occipital Lobe, 7: Dorsolateral prefrontal cortex, 8: Superior Parietal Lobule, 9: Supplementary motor area, 10: Right extrastriate body area, 11: Occipito-parietal cortex, 12: Cerebellum, 13: Primary motor cortex, 14: Cuneus, 15: Middle temporal gyrus / Visual area 5, 16: Primary somatosensory area 3a, 17: Parietal operculum, 18: Cerebellar vermis, 19: Pedunculo-pontine nucleus / Mesencephalic locomotor region, 20: Posterior hippocampus, A = Intraparietal sulcus (Cremers et al., 2012), B = Parieto-occipital sulcus (Cremers et al., 2012). Anatomical location of brain regions may be approximate for purposes of visual display. Dotted lines delineate subcortical structures. MI: Motor Imagery, PKD: Parkinson's Disease, HPs: Healthy Participants

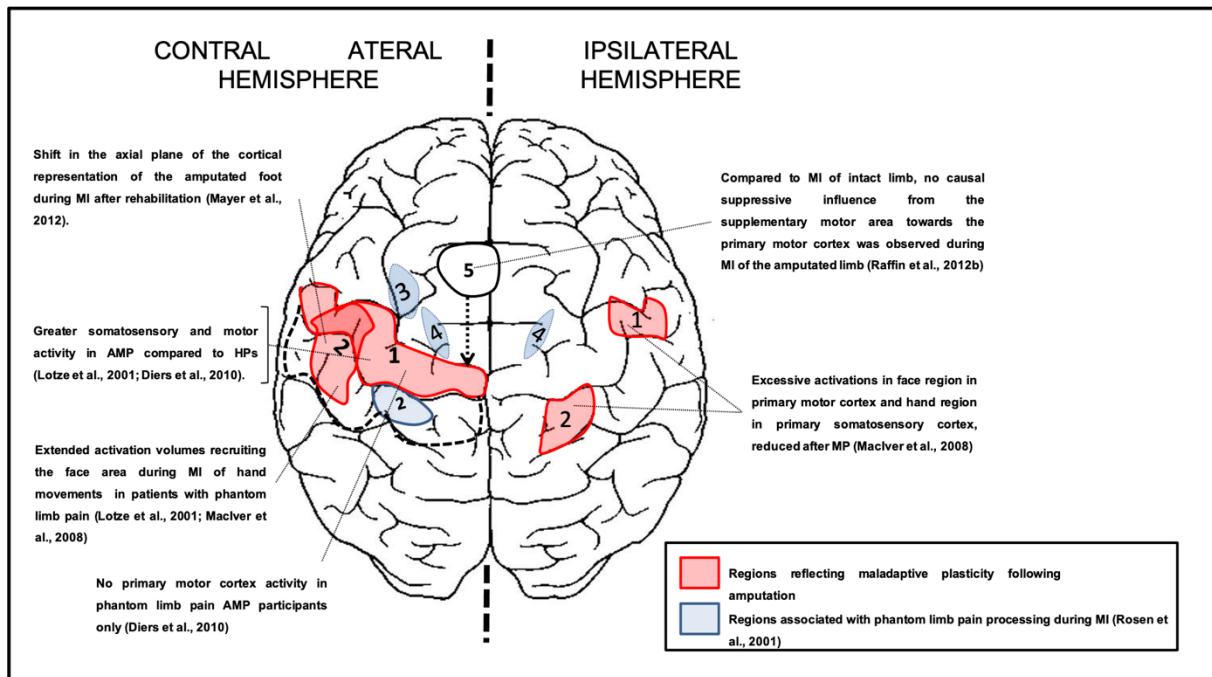


**Fig. 5.** Brain activity during MI of affected limb reflecting motor symptoms or the effect of treatment in Parkinson's disease participants. Information is based on the results of brain imaging MI studies. 1: Precuneus, 2: Lingual Gyrus, 3: Pre-motor cortex (dorsal and lateral), 4: Anterior cingulated cortex, 5: Brodmann 3a, 6: Dorsal pre-motor cortex, 7: Thalamic ventral intermediate nucleus, 8: Supplementary motor area, 9: Inferior frontal gyrus, 10: Putamen, 11: Dorsolateral pre-frontal cortex, 12: Occipital cortex, 13: Mesencephalic

locomotor region, 14: Posterior parietal cortex / precuneus, 15: Pre-supplementary motor area. Anatomical location of brain regions may be approximate for purposes of visual display. Dotted lines delineate subcortical structures. MI = Motor Imagery, PKD = Parkinson's Disease

MI of actions involving an amputated limb recruits effector-specific brain regions within the somatosensory and motor *homunculi*, *i.e.*, areas previously dedicated to the control of the amputated limb (Ersland et al. 1996; Hugdahl et al. 2001; da Paz et al. 2000). Raffin et al. (2012b) provided the first fMRI evidence for a functional distinction between MI and attempted PP with an amputated upper limb. The neuro-architecture of MI was similar whether MI involved the healthy or amputated limb: “*The network (...) did not appear to change according to which hand (phantom or intact) performed the task*”, Raffin et al. (2012b), p. 537. Overall, functional equivalence between MI and PP is preserved after AMP. MacIver et al. (2008) observed that MP literally reversed cortical reorganizations and alleviated phantom limb pain. MI of movements with the missing upper limb after training no longer resulted in excessive bilateral activations in the primary motor and somatosensory face regions, nor within ipsilateral hand area within the primary somatosensory cortex (Fig. 6).

Extensive primary somatosensory and motor reorganizations occur after AMP. Expansion of the cortical surface corresponding to unaffected body parts towards adjacent deafferented cortical sites is well-documented (Knecht et al. 1996; Pascual-Leone et al. 1996; Karl et al. 2001; Ramachandran et al. 2010). These cortical changes were associated with occurrence of phantom limb pain (*e.g.*, Flor et al. 1995; Lotze et al. 2001), and termed “*maladaptive plasticity*”. Maladaptive plasticity is reflected in the cerebral substrates of MI (Fig. 6). Lotze et al. (2001) observed that AMP participants with phantom limb pain recruited the face area within the sensorimotor cortex during MI of hand movements, a pattern absent in pain-free AMP subjects. Diers et al. (2010) noted that only AMP participants with phantom limb pain failed to elicit primary sensorimotor activity during MI of actions executed with the phantom limb. MI thus seems to replicate a pathological state where the motor system fails to elicit the sensorimotor demand elicited by MI. MI mirrors neuroplasticity-related differences between AMP participants with and without phantom limb pain. Rosen et al. (2001) attempted to segregate the cerebral substrates underlying phantom limb pain in a case study (Fig. 6).



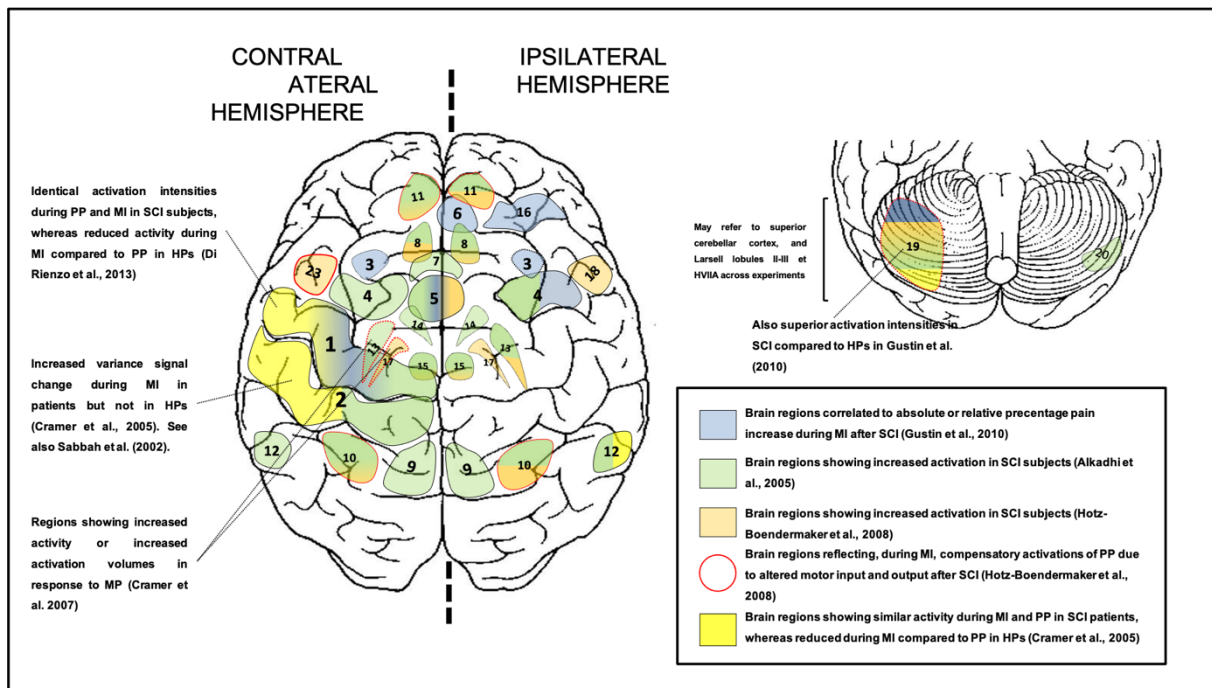
**Fig. 6.** Brain activity during MI of movements with the amputated limb reflecting neuroplasticity after amputation. Information is based on the results of brain imaging MI studies. 1: Primary motor cortex, 2: Primary somatosensory cortex, 3: Left insula, 4: Ventral posterior lateral thalamic nucleus, 5: Supplementary motor area. Anatomical location of brain regions may be approximate for purposes of visual display. AMP: amputee, MI: Motor Imagery.

Data support preservation of motor representations after SCI (Sabbah et al. 2002; Sabbah et al. 2000; Lacourse et al. 1999; Alkadhi et al. 2005; Hotz-Boendermaker et al. 2008). In spite of consistent cerebral reorganizations due to deafferentation and deafferentation (for a review, see Kokotilo et al. 2009), cerebral patterns of activity during MI is largely similar to that in HPs (Gustin et al. 2010; Hotz-Boendermaker et al. 2008; Alkadhi et al. 2005; Cramer et al. 2005; Sabbah et al. 2002). A SCI participant even showed similar changes as HPs in cerebral recruitment during MI of familiar vs. unfamiliar actions (*i.e.*, recruitment of the pre-motor network only during MI of familiar motor acts; Olsson 2012). Nonetheless, quantitative differences were also reported in SCI subjects. Compared to HPs, greater activity was observed within the contralateral primary sensorimotor cortex during MI of spared (Sabbah et al. 2002) and impaired movements (Alkadhi et al. 2005; Hotz-Boendermaker et al. 2008; Gustin et al. 2010). Reduced activation volumes were also reported (Sabbah et al. 2002; Cramer et al. 2005). Discrepancies might account for the mode of stimulus delivery and the type of MI task (*i.e.*, with or without visual cueing; analytic vs. functional task). Hotz-Boendermaker et al. (2008) noted that

MI reproduced compensatory activations assumed to reflect altered “*input and output*” during PP due to SCI (Fig. 7). Lacourse et al. (1999) observed that MI and attempted PP elicited analogous EEG responses from the pre-motor and primary motor cortices in participants with paraplegia and quadriplegia during MI of infra-lesional actions. Conversely, the time course of EEG responses remained dissociable between the two tasks in HPs, as revealed by cross-correlation analyses. In the same vein, Cramer et al. (2005) evidenced that the reduction in primary motor cortex activation observed during MI compared to PP in HPs was absent in participants with SCI. Alkadhi et al. (2005) reported that during MI of foot movements, SCI participants recruited neural networks underlying *both* PP and MI in HPs with higher activation intensities. Higher levels of primary sensorimotor activity and poor changes in primary motor cortex activation intensities between MI and PP suggests *strengthened* functional equivalence after SCI (Fig. 7). The hypothesis of weakened motor inhibition was advanced (Lacourse et al. 1999). SCI participants may no longer require inhibiting motor output during MI since spinal damage prevents from transmission of the neural orders to the peripheral effectors (Lacourse et al. 1999). Albeit this hypothesis remained an inference, a direct link between sites of inhibitory activity during MI and primary motor cortex activation during MI was recently evidenced with magnetoencephalography (Di Rienzo et al. 2013).

Only one study investigated MP-induced neuroplasticity after SCI (Cramer et al., 2007). SCI participants benefited from MP to improve performance of spared motor functions (*i.e.*, increased speed of execution of sequential tongue movements). Motor improvements were associated with increased putamen and globus pallidus activation (Fig. 7; Cramer et al. 2007). MP was also delivered to alleviate neuropathic pain after SCI, which was associated with maladaptive plasticity within the primary somatosensory and motor cortices (Wrigley et al. 2009; see Gustin et al. 2008 for a brief discussion). MI of purely analytic infra-lesional movements failed to alleviate, and worsened below-level neuropathic pain (Gustin et al. 2008). Gustin et al. (2010) evidenced MI-related activations within the pain neural matrix which correlated with pain increases (Fig. 7). It is possible that MI elicits a conflicting state of body awareness due to mismatching between motor output and sensory input after SCI, thus underlying emergence of neuropathic pain (Moseley 2007; Harris 1999). MI of walking, conversely, decreased at- and below-level neuropathic pain, yet to a lesser extent than walking within a virtual environment (Moseley 2007). Functional tasks involving congruent representations of the whole body might contribute to restore coherence in a mismatching state of body awareness (Moseley 2007; Harris 1999).

Isolated MI of neurologically impossible movements might cause an opposite effect (Gustin et al. 2008; Gustin et al. 2010).



**Fig. 7.** Schematic representation of brain activity during MI of infra-lesional movements in SCI participants reflecting adaptive neuroplasticity. Study by Olsson et al. (2012) was considered reflecting activity-dependent rather than SCI-dependent neuroplasticity and not included in the figure. Information is based on the results of brain imaging MI studies. 1: Primary motor cortex, 2: Primary somatosensory cortex, 3: Anterior insula, 4: Premotor cortex, 5: Supplementary motor area, 6: Perigenual anterior cingulate cortex, 7: Pre-supplementary motor area, 8: Cingulate motor area, 9: Superior parietal cortex, 10: Inferior parietal cortex, 11: Pre-frontal cortex, 12: Secondary somatosensory cortex, 13: Putamen, 14: Caudate nucleus, 15: Thalamus, 16: Dorsolateral pre-frontal cortex, 17: Globus pallidus / Pallidum, 18: Pre-motor ventral, 19: Cerebellar cortex, 20: Larsell lobules HVIIA. Anatomical location of brain regions may be approximate for purposes of visual display. Dotted lines delineate subcortical structures. PP: Physical Practice, MI: Motor Imagery, HPs: Healthy Participants, SCI: Spinal Cord Injury

#### 4.3.2.2.2 Implicit motor imagery

Following STR, Yan et al. (2012) observed impaired cognitive processing during the different cognitive sub-stages of implicit MI (*i.e.*, spatial encoding and mental rotation), due to weaker frontal, central and parietal

activity within the stroke-affected hemisphere. In PKD participants, fMRI recordings revealed that complex tasks involving PKD-affected limbs recruited a compensatory visual network (*i.e.*, including the extrastriate visual area and the parieto-occipital cortex; Helmich et al. 2007). These findings were recently confirmed by TMS (van Nuenen et al. 2012). Interestingly, tremor in PKD improved neural function within a cortical-subcortical somatosensory and pre-motor network underlying increased implicit MI performance. The ventral intermediate nucleus showed both tremor-related and implicit MI-related activity. The ventral intermediate nucleus projects to the somatosensory cortex, where the activity was superior during implicit MI in tremulous compared to non-tremulous PKD subjects (Helmich et al. 2011).

#### 4.3.3 *Motor imagery profiles based on neurophysiological data*

### **5 MI capacities in clinical populations**

We reviewed to which extent psychological, behavioral and neurophysiological correlates of MI were affected by neurologic disorders. Several neurologic MI (and implicit MI) *profiles* emerged based on psychometric and behavioral evaluations. Psychometric and behavioral correlates of MI yielded either preserved or selective MI deficits corresponding to the motor impairments (Tables 4-5). Two additional profiles were specific to behavioral evaluations (*i.e.*, temporal coupling *preserved* but reflecting the timing of slower motor performance on impaired actions; and *impaired* temporal coupling *irrespective* of the actual motor deficit; Table 5). Neurophysiological findings systematically underlined differences with HPs when participants with motor disabilities engaged into MI of clinically affected movements. Functional equivalence was nonetheless preserved, MI recruiting the reorganized motor networks of PP. Brain correlates thus mirrored brain changes due to the neurologic disease or related adaptive neuroplasticity (Fig. 3-7). This might account for the large prevalence of MI profiles reflecting actual motor impairments (Tables 4-5). Brain imaging data thus strongly challenged the assumption that movements which can no longer be physically performed “*cannot be imagined in a way that is necessary for functional equivalence*” (Olsson and Nyberg 2010).

#### 5.1 *Motor imagery profile after spinal or peripheral damage*

When the neurologic pathology did not involve *direct* cerebral damage, *i.e.*, after SCI and AMP, psychological and behavioral correlates of MI are poorly affected (Tables 4-5). Changes might occur in AMP, but were restricted to MI of the missing limb (Table 4-5). Brain imaging investigations of MI in SCI and AMP participants revealed that the cerebral networks underlying PP and MI were reorganized *in parallel*. Cerebral

activity during MI largely overlaps with that in HPs in SCI, or with that in the unaffected limb in AMP subjects. An interesting finding in AMP is that behavioral and neurophysiological correlates of MI support integration of functional limb prosthesis to the body schema (Lotze et al. 2001; Malouin et al. 2009a; Nico et al. 2004). AMP and SCI primarily affect the cerebral correlates of MI through *quantitative* changes related to adaptive neuroplasticity. Since there is no direct cerebral damage, motor representations can be alimanted by other sources of sensory input than proprioceptive afferents from impaired body parts (*e.g.*, action observation in SCI participants and sensory input from unaffected body parts in AMP participants). This would explain preservation of psychometric and behavioral MI performance.

## 5.2 *Motor imagery profile after cerebral damage and disorders*

When the neurologic pathology involved direct damage to cerebral structures, *i.e.*, after STR and PKD, psychological and behavioral correlates of MI tend to differ from HPs. Deficits often related to clinical impairments. STR and PKD both induce primarily *qualitative* changes in cerebral recruitment during MI. Brain imaging data revealed compensatory patterns of cerebral activity, presumably reflecting adaptive neuroplasticity. Importantly, compensatory neural circuits can be targeted by MP. Changes in brain activity during MI and implicit MI compared to HPs might account for psychometric and behavioral MI deficits. Yet, brain changes do not necessarily imply MI deficits (Table 4-5). Compensatory neural networks may vicariate anterior implicit MI functions, thus resulting in spared implicit MI performance (*e.g.*, van Nuenen et al. 2012; Johnson et al. 2002).

## 6 **Theoretical implications**

### 6.1 *Integrating cognitive and motor deficits within motor imagery evaluation frameworks*

Present literature analysis revealed that motor incapacities were strong and reliable predictors of MI capacities after both acute and chronic and progressive neurologic disorders. MI was preserved, or altered according to motor impairments in more than 85 % of MI studies. We advocate that MI evaluation frameworks should take into account current motor capacities when determining the standards for “*high*” MI capacities in these populations. More precisely, a rigorous framework should encompass three distinct levels of analysis to delineate the MI profile:

- i. Reference to MI correlates for an action that the participant can perform physically (*e.g.*, movements involving spared effectors in participants with lateralized motor deficits, MI of movements innervated above the neurologic level of SCI)
- ii. Reference to MI evaluation standards (*e.g.*, temporal equivalence, scoring threshold for MI questionnaires, recruitment of motor / pre-motor sites during MI, etc.)
- iii. Reference to MI performance in HPs undergoing similar evaluations

Also, most reviewed experiments screened participants with severe cognitive deficits, usually on the basis of the “Mini Mental State Evaluation” (Folstein et al. 1975). Independent testing of working memory in MI designs (Malouin et al. 2004a; Malouin et al. 2012; Hovington and Brouwer 2010) and body schema integrity in implicit MI designs (Coslett 1998; Daprati et al. 2010; Tomasino et al. 2003; Nico et al. 2004) may be legitimate on the basis of available scientific data.

## 6.2 Combining evaluation methods to determine the MI profile

MI and implicit MI paradigms address different components of motor cognition (see section 2.2 for a brief discussion). Among studies assessing both MI and implicit MI performance within the same sample of participants (6 studies involving STR or PKD participants), results between the two evaluation methods were congruent in 40 % of cases (*i.e.*, assessments yielded similar neurologic MI profiles). Of importance, MI profiles cohabitated within a same clinical population for a given evaluation method (Tables 4-5). No disease-related characteristics unambiguously predicted such variability (section 8.2). Some MI profiles were more prevalent than others for a given neurologic disease (Tables 4-5; STR participants presenting higher variability in MI profiles, which might reflect the variability of the STR lesions and resulting neuroplasticity). In studies involving more than one MI evaluation method (*i.e.*, psychometric, behavioral and neurophysiological), neurologic MI profiles were redundant across evaluation methods in only 45 % of cases. Clinical data confirmed that each type of evaluation addressed a distinct component of MI – hence are complementary (Guillot and Collet 2005a).

As stated by Dettmers et al. (2012): “*There is no single and uniform test that can categorize patients’ ability or disability to perform MI*”. Literature data strongly supports this view, and, for clinicians, determining the neurologic MI profile may be a relevant and justified approach to this issue. Assessing MI profiles would ideally require a battery of tests combining psychological, behavioral and neurophysiological methods. As subjective and subjective MI assessment methods “*generally tend (...) to dissociate*” these should be combined

*in priority* (Dettmers et al. 2012; Lequerica et al. 2002). For instance, *at least* psychometric and behavioral methods should be used (see Dickstein et al. 2013 for a perfect illustration). A remarkable assessment battery used to determine participant's inclusion within MI / MP experiments is the “*chaotic*” assessment battery (Simmons et al. 2008; Sharma et al. 2008; Sharma et al. 2009a; Sharma et al. 2009b). There are nonetheless several shortcomings related to the use of this method in clinical research (Supplementary material).

### 6.3 *Crossing the bridge between psychometric and behavioral motor imagery correlates and functional equivalence*

A major finding of the present review is that neurologic deficits resulted in specific patterns of altered subjective experience of MI or temporal equivalence, respectively impacting psychometric and behavioral evaluation data in spite of preserved functional equivalence. Relating psychometric and behavioral MI data to functional equivalence patterns is therefore an *absolute necessity* in order to promote further translations from bench to bedside in clinical MI research, which appeared quite limited at this point. This should contribute to delineate the optimal rules for control of MI training in order to promote MP-dependant neuroplasticity. For instance, there may be a positive correlation between MI vividness and primary somatosensory and motor cortex stimulation during MI of impaired actions in AMP and SCI subjects (Lotze et al. 2001; Alkadhi et al. 2005). Confalonieri et al. (2012) described a negative correlation between MI ease of the affected hand (*i.e.*, kinesthetic and visual MIQ-RS subscores) and the percentage of fMRI blood oxygenation level-dependant signal changes within contralesional sensorimotor and pre-motor cortices and ipsilesional hippocampus. Data by Confalonieri et al. (2012) bring decisive insights to current understandings of MI ability in the context of clinical rehabilitation: MI may stimulate primary sensorimotor and pre-motor networks in spite of poor MI ease. Kimberley et al. (2006), however, observed comparable patterns of sensorimotor and pre-motor cortex activity in subgroups of STR participants with high and one with low MI ease scores (see also Cramer et al. (2005) for analogous results in SCI participants). Overall, the relationship between behavioral and psychometric correlates of MI and functional equivalence with PP and MI remains unexplored, and results may go against preliminary conceptions.

## 7 **Practical implications**

At this point, the high variability of evaluation methods encountered in clinical MI experiments hampers prescriptive generalizations related to ‘good MI evaluation practice’. Nonetheless, theoretical principles for MI evaluation, rather than practical prescriptions for clinicians, emerged (section 6). While the development

of further standardized procedures must be encouraged, and their use be preferred for homogeneity and reproducibility of results across paradigms, many evaluation techniques can be adapted to the specific context of each clinical experiment (Table 3), and provide reliable information concerning the neurologic MI profile if standardized assessment procedures meeting protocol's requirements in terms of specificity are unavailable<sup>5</sup>. There may also be strong complementarities between the two approaches. For instance, standardized behavioral tests can be relevantly combined with ease and vividness self-reports (see Heremans et al. 2011 for a relevant illustration).

### 7.1 Evaluation methods in mental practice studies

In MP studies, psychological and behavioral MI evaluations suited purposes of *i*) preliminary MI assessment and *ii*) control of MP (see section 2.1). The two evaluation methods were, however, rarely used in concurrently (see section 2.2). Their combination should be encouraged to provide complementary information on MI quality (Table 3, section 6.2). Evaluation procedures, as long as they integrate key principles for reliable clinical MI evaluations (Table 2, section 6), are infinite in essence and should not be *a priori* restricted to existing standardized tests.

Albeit obvious, MI evaluations in MP designs should be *primarily* conducted on tasks involving peripheral effectors involved in MP programs, *e.g.*, simple single-joint actions involving effectors impaired by the pathology (*e.g.*, analytic motor functions targeted in physiotherapy) or goal-directed actions with a clear functional purpose (*i.e.*, finalized motor sequences usually targeted in occupational therapy) of graded complexity along the course of the intervention (Dickstein et al. 2004; Dunskey et al. 2006; Craje et al. 2010; Grangeon et al. 2012b; Beaumont et al. 2011; Braun et al. 2008). Self-report ratings and chronometric recordings are easily adaptable to such motor tasks. Caution should be exercised as data might mirror motor impairments, yet should not be considered markers of *degraded* MI quality (section 6.1). Task duration should ideally range from 5 to 25 s (Table 2), to avoid deleterious effects on isochrony (Guillot et al. 2012b). Finally, MI durations must be controlled during MP, and resemble those of the corresponding motor performance to achieve the desired transfer effects on motor behaviors (see data by Louis et al. 2008 for a relevant illustration).

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<sup>5</sup> There are many examples in the MP literature of such tests with STR, PKD, SCI and AMP people.

Standardized psychometric and behavioral assessments initially developed for HPs, as well as implicit MI evaluations, may not convey critical information regarding the specific MI skills required to benefit from MP. Such tests should nonetheless not be excluded from MP designs, but preferentially used for the purpose of preliminary assessments, or to familiarize participants with MI (*e.g.*, Dominey et al. 1995; Thobois et al. 2002; Snijders et al. 2011). Standardized psychometric and behavioral evaluations provide general information concerning MI capacities, and are reproducible. In the case of persons with severe motor impairments, questionnaire items referring to actions that participants can no longer perform, or with difficulties, should be considered separately in data analysis, or even removed (Dickstein et al. 2004; see also KVIQ-10, which provides a simplified version of the KVIQ; Malouin et al. 2007; Schuster et al. 2012c). To summarize, standardized methods may primarily suit purposes of preliminary MI assessments, whereas non-standardized psychometric and behavioral evaluations may be particularly relevant to control of MP.

## 7.2 *Evaluation methods in motor imagery studies*

In MI studies, assessment methods were regularly combined (*i.e.*, 50 % of cases; *e.g.*, use of chronometric measures to ensure phase-locked recordings of brain activity during MI). When only one evaluation method was being used, evaluations were typically conducted across several tasks with varying motor and perceptual demands (*e.g.*, Sirigu et al. 1996; Johnson et al. 2002).

### 7.2.1.1 *Explicit motor imagery experiments*

Detailed information about the MI modality was missing in 39 % of brain imaging studies. This is surprising as different MI modalities involve different levels of functional equivalence with PP, particularly with regards to the recruitment of primary somatosensory and motor structures (Solodkin et al. 2004; Guillot et al. 2009; Lorey et al. 2009). To assist practitioners in the elaboration of fruitful MP designs, future MI studies should address the neural underpinnings of different MI modalities, along with their psychometric and behavioral correlates (see section 6.3). For instance, people with neurologic diseases may present reduced capacities to use first-person perspective, compared to more external modalities, as revealed by psychometric evaluations (Li 2000; Dettmers et al. 2012; Schuster et al. 2012c). Furthermore, most reviewed experiments involved MI of self-paced movements, and the basic movement parameters of MI were insufficiently described (*e.g.*, speed, repetition rate, amount of force). This may introduce uncertainties in data interpretation, because

movement parameters are known to be reflected, for instance, in the brain correlates of MI in HPs (Sauvage et al. 2013).

Reviewed MI studies consisted of *transversal* experiments focusing on subjects exhibiting stabilized motor impairments (section 2.1). MI research protocols should now consider determining how the psychological, behavioral and neurophysiological correlates of MI are altered in a *longitudinal* fashion, *e.g.*, during acute, subacute and chronic stages of neurologic disorders. For instance, neuroimaging MI findings may be a function of time after injury (section 4.3.2.2.1). At this point, we only found one study explicitly addressing this issue, on the basis of single-case chronometric evaluations (Sabate et al. 2007). There is thus a literature gap in this area that needs to be addressed in future experiments.

#### 7.2.1.2 *Implicit motor imagery experiments*

Guillot et al. (2012b) underlined that contrary to MI experiments, implicit MI paradigms required forming mental images as fast as possible. MP designs almost never involved implicit MI tasks. Implicit MI evaluations appeared of primary interest for fundamental research issues related to body schema integrity (Nico et al. 2004; Coslett 1998). Nonetheless, data in HPs support that implicit MI such as mental rotation of body parts may not systematically involve *motor-related* cognitive strategies (Ionta et al. 2012; Conson et al. 2012; Brady et al. 2011; Ni Choisdealbha et al. 2011; Hoyek et al. 2013). These tasks may be solved using purely visual / allocentric cognitive strategies (Hoyek et al. 2013). Data in STR, SCI and AMP participants suggest that MI may promote visual, rather than motor, cognitive strategies. Daprati et al. (2010) evidenced that severely affected STR participants used visual strategies to compensate deficient access to their body schema. STR subjects with mild motor deficit, however, kept referring to their body schema, thus showing implicit MI deficits corresponding to their motor incapacities. Likewise, Nico et al. (2004) argued that reduced implicit MI performance in AMP participants could :

*“Reflect use of a (...) visual-spatial strategy rather than a motor-kinesthetic one” and no longer “use the strategy of mentally rotating their own hand to match the stimulus and choose instead to rotate the stimulus-hand as an object”.* Nico et al. (2004), p. 131., (see also data by Curtze et al. 2010).

To control for use of visual strategies during implicit MI, oral debriefs were used (Nico et al. 2004). Implicit MI data in PKD subjects revealed a neural circuitry for *visual* compensation during implicit MI (van

Nuenen et al. 2012; Helmich et al. 2007), while after SCI, Fiori et al. (2013) provided evidence that implicit MI may no longer involve manipulation of motor representations at all.

Accordingly, extreme caution should be taken when interpreting implicit MI results in clinical populations with severe and chronic motor deficits. Albeit not intuitive, high implicit MI performance (*e.g.*, absence of burst in error rate during recognition of body limbs presented in unfamiliar orientations) may reflect body schema disorders. Particularly, it may indicate use of other strategies than manipulation of motor representations (Fiori et al. 2013; Daprati et al. 2010; Curtze et al. 2010). Complex implicit MI tasks finally appeared more suitable to unveil implicit MI limitations in STR, PKD, SCI and AMP subjects (Nico et al. 2004; Johnson et al. 2002; Helmich et al. 2007; Fiori et al. 2013).

## **8 Participant's eligibility to mental practice**

### *8.1 Motor imagery*

In spite of a large body of neuroscience research, it remains unexplored whether high MI skills are necessary to benefit from MP. As recently pointed out by Braun et al. (2011): “*at this point (...) it is not known if being able to perform mental imagery necessarily equates to benefiting from it in clinical practice*”. Accordingly, screening subjects on the basis of their MI capacities should also be done with *extreme* caution.

Nonetheless, could screening participants on the basis of their MI capacities be relevant? The possible induction of activity-dependant neuroplasticity by MI training, *because of functional equivalence with PP*, remains the central component of fruitful MP interventions in rehabilitation, even in the management of non-motor disabilities (*e.g.*, MacIver et al. 2008). An important literature-driven implication is that determining eligibility to MP based on MI capacities should not be screening for high MI skills *per se*, but determining whether functional equivalence is preserved based on the neurologic MI profile. Along this perspective, implicit MI tests have poor predictive power. For instance, MI experiments revealed that the psychometric, behavioral and neurophysiological correlates of MI, when performed with a high degree of functional equivalence with PP in neurologic populations, *differed* from those in HPs due to pathologic / adaptive brain changes. The systematic literature review leads to the postulate that, in STR, PKD, SCI and AMP people, *i)* intact MI capacities (*i.e.*, psychometric and behavioral MI profiles n° 1 in Tables 4-5, or identical brain activity during MI as HPs; see sections 4.1.3, 4.2.1, 4.3.3) or *ii)* with specific MI deficits corresponding to the effect of the disease on actual motor capacities (*i.e.*, psychometric MI profile n° 2 in Table 4, behavioral MI profiles n° 2 - 3 in Table 5, see

also Fig. 3 - 7 for brain activation during MI reflecting reorganization of PP motor networks), may reflect intact functional equivalence.

## 8.2 *Characteristics of the neurologic disease*

Present literature review did not *unambiguously* afford to isolate neurologic characteristics (*e.g.*, lesion type, severity) that hampered MP efficacy. To our knowledge, only one study established a link between the nature of the neurologic damage and the clinical outcome of MP. Butler and Page (2006) reported that a STR participant suffering from a large left parietal cortex lesion failed to benefit from MI training because of reduced MI capacities. Subjects with parietal strokes were *a priori* excluded from some MP studies (Page et al. 2011b; Page et al. 2011a). Nonetheless, “*screening on the basis of lesion location might be insufficient*” (see also conclusions by Schuster et al. 2012c; citation by Simmons et al. 2008). Indeed, STR damage to parietal regions did not systematically result in degraded MI capacities across reviewed experiments. Neuroplasticity occurs after STR, which might allow spared brain regions to be “*progressively vicarious*” of the functions assumed by damaged neurons (Rossini and Pauri 2000). This advocates for *more systematic MI evaluations* in future MP protocols, which should be clearly preferred to *a priori* eligibility statements not being supported by data.

By contrast, the repercussion of the neurologic pathology on high-order cognitive functions quasi-systematically hampered the benefits of MP. Particularly, working memory impairment in persons with STR, that nonetheless successfully completed the TDMI test (Table 2), negatively correlated with MP efficacy (Malouin et al. 2004a). In PKD participants, Yaguez et al. (1999) established a direct link between working memory impairments and negative outcome of MP, while Braun et al. (2011) observed that PKD subjects with mild cognitive impairments benefited more from MP than PKD subjects with severe cognitive deficits.

## 8.3 *Repeated motor imagery evaluations*

STR, SCI, PKD and AMP subjects who benefited from restorative interventions improved their MI capacities (Deutsch et al. 2012; Butler and Page 2006; de Vries et al. 2011; Stevens and Stoykov 2003; Cunnington et al. 2001; Dominey et al. 1995; MacIver et al. 2008; McAvinue and Robertson 2011; Beaumont et al. 2011; Gustin et al. 2010). Participants should thus not be excluded on the basis of a single MI evaluation. This advocates for *repeated* assessments to define the baseline level of mental performance. MP experiments frequently involved repeated PP assessments before delivery of MP. Repeated MI assessments could therefore be easily included, thereby providing adequate control of learning effects. If MI is assessed once, extended

familiarization sessions should be considered (see Wondrusch and Schuster 2013 for a standardized procedure). For instance, some authors trained participants to perform MI until they reached the desired level of vividness or isochrony (e.g., Lotze et al. 2001; Battaglia et al. 2006; Cremers et al. 2012).

## **9 General conclusion**

Neurologic disorders such as STR, SCI, PKD and AMP impact the psychological, behavioral and neurophysiological correlates of MI, thus resulting in highly specific profiles of MI capacities. Functional equivalence between MI and PP was overall preserved. However, cerebral activity reflected structural and functional changes due to neuroplasticity. Brain changes were echoed in a congruent fashion in the psychometric and behavioral correlates of MI. Further research is needed to determine the psychometric and behavioral markers of functional equivalence in clinical populations. MI capacities may be degraded *per se* in some specific cases, but primarily due to the effect of the neurologic pathology on higher order cognitive functions. Such patterns of MI impairments were only observed in certain cases of STR and PKD. After AMP and SCI, cerebral structures remain intact but reshaped. Disturbances of body schema primarily affect implicit MI, particularly during complex tasks involving manipulation of mental representations of affected body parts. These results have strong implications regarding the means of assessment and control of MI in future experiments. A large number of methods allow rigorous MI assessments in MI and MP designs, but these should be combined to determine the neurologic MI profile in the perspective of eligibility to MP.

**Conflict of interest**

The authors declare no conflict of interest.

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### **Supplementary material: Chaotic motor imagery assessment**

A remarkable assessment battery used to determine patient's eligibility to motor imagery (MI) studies is the "chaotic" assessment battery developed by Sharma and collaborators and then used in many clinical studies (Heremans et al. 2012; Heremans et al. 2011; Sharma et al. 2009a; Sharma et al. 2009b; Simmons et al. 2008). "Chaotic" MI refers to MI deficits in the sense of an "*inability to perform motor imagery accurately or temporal uncoupling of otherwise accurate imagery*" (Simmons et al., 2008). The "chaotic" MI assessment battery involves i) an implicit MI task (*i.e.*, determining laterality of body parts with an accuracy superior to 75 %), ii) a psychometric congruency test and iii) a behavioral test (*i.e.*, Break test; Table 2). The chaotic assessment is relevant to screen for high MI capacities. There are nonetheless several shortcomings related to the use of this method in clinical populations.

In MI training designs, screenings on the basis of an implicit MI test is debatable, since MI training does not involve implicit MI practice. In MI designs, Sharma et al. (2009) excluded 5 STR participants out of 20 (*i.e.*, 25%) prior to enrollment due to incapacity to elicit during MI a break point equivalent or inferior to the break point recorded during PP (*i.e.*, the "chaotic" standard for the break test). 23 % of HPs were also declared unable to perform MI on the basis of "chaotic" assessment (*i.e.*, 2 HPs had superior break points during MI than during PP, while 2 others had implicit MI performance below the accuracy threshold). Accordingly, the method seems highly stringent, and does not appear to screen for MI deficits related to the neurologic disease. Simmons et al. (2008) excluded 3 patients out of 10 (*i.e.*, 30%) on the basis of superior break point during MI compared to PP (*i.e.*, superior by 12 – 32 %), whereas patients with severely inferior break point (*i.e.*, inferior until 42 %) during MI compared to PP were declared eligible to MI training. Why, in "chaotic" standards of the break test, slight overestimation is not allowed when severe underestimation is permitted is unknown. With such standards, "Chaotic" assessment may exclude STR participants which could have benefited from MI training. For instance, Butler and Page (2006) reported that some patients with higher break point during MI compared to PP at on the break test (*i.e.*, participants ineligible to MP according to the "chaotic" standards). They nonetheless benefited from MP. Further, MP elicited cerebral reorganizations, as revealed by fMRI.

The "chaotic" battery remains a relevant approach to screen for high MI capacities, and a remarkable attempt to provide objective MI evaluations in both HPs and clinical populations. However, *standards* used to

determine whether MI is “chaotic” or not in clinical populations should be adapted with reference to “neurologic” MI profiles.

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