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## **Effect of object substitution, spontaneous compensation and repetitive training on reaching movements in a patient with optic ataxia**

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1           **EFFECT OF OBJECT SUBSTITUTION, SPONTANEOUS**  
2           **COMPENSATION AND REPETITIVE TRAINING ON REACHING**  
3           **MOVEMENTS IN A PATIENT WITH OPTIC ATAXIA**

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23

## **ABSTRACT**

24 We report the case of M.B. who demonstrated severe optic ataxia with the right hand following  
25 stroke in the left hemisphere. The clinical picture may shed light on both the pathological  
26 characteristics of reaching and grasping actions, and potential rehabilitation strategies for optic  
27 ataxia. First, M.B. demonstrated a dissociation between severely impaired reaching and  
28 relatively spared grasping and tool use skills and knowledge, which confirms that grasping may  
29 be more intermingled with non-motoric cognitive mechanisms than reaching. Besides, M.B.'s  
30 reaching performance was sensitive to movement repetition. We observed a substitution effect:  
31 Reaching time decreased if M.B. repeatedly reached toward the same object but increased when  
32 object identity changed. This may imply that not only object localization but also object  
33 identity, is integrated into movement programming in reach-to-grasp tasks. Second, studying  
34 M.B.'s spontaneous compensation strategies ascertained that the mere repetition of reaching  
35 movements had a positive effect, to the point M.B. almost recovered to normal level after an  
36 intensive one-day repetitive training session. This case study seems to provide one of the first  
37 examples of optic ataxia rehabilitation. Reaching skills can be trained by repetitive training  
38 even two years post-stroke and despite the presence of visuo-imitative apraxia.

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## **KEYWORDS**

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Optic ataxia; reaching; grasping; rehabilitation; apraxia.

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## **PRINTING**

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We recommend printing in black-and-white.

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## **1. AIMS OF THE PRESENT STUDY**

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This study reports the case of M.B., a stroke patient who suffered from optic ataxia after unilateral lesions of the left occipitoparietal regions. M.B. demonstrated severely impaired reaching movements with his right hand but relatively spared grasping abilities and normal tool use skills and knowledge. Besides, clinical investigation showed a substitution effect: Changing the identity of the object had an adverse influence on reaching time whereas repeatedly reaching toward the same object improved performance – with object location being fixed. In an attempt to understand this phenomenon and infer potential rehabilitation methods we studied M.B.'s spontaneous compensation strategies and found that performance benefited from mere movement repetition. A few hours of repetitive reaching movements led to sustainable decrease in reaching time. So, this case study provides insight into the pathological characteristics of optic ataxia, and paves the way for future rehabilitations.

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## **2. THEORETICAL BACKGROUND**

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Using a tool requires three steps: 1) reaching the tool (e.g., a hammer); 2) grasping the tool; 3) using the tool with an object (e.g., pounding a nail). Each of these steps may call for different motor and/or cognitive mechanisms.

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### ***2.1. REACHING, GRASPING AND USING COMPONENTS OF ACTION***

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#### **2.1.1. Reaching**

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Reaching movements correspond to the hand trajectory toward the tool to be grasped, independently of how the tool is subsequently grasped. They are proximal-to-distal, fast movements with a straight line and a bell shape speed profile (Karniel & Inbar, 1997). In normal human activity, reaching movements rely mainly on visuo-motor connections (Jeannerod, 1986). They are thought to depend on characteristics of the body (e.g., proprioceptive input; Ghez, Gordon, & Ghilardi, 1995) rather than of the object (except for its position and orientation relative

68 to the body) in that they connect the body and the object. While reaching movements are most  
69 frequently programmed on a top-down basis (i.e., the intention), they are also driven by bottom-  
70 up real-time corrections (Grea et al., 2002) seeing that rapid changes in target location modify  
71 movement kinematics (Pisella et al., 2000). Therefore, reaching is automatically elicited but  
72 voluntarily activated. Reaching movements under visual control rely on the activity of the  
73 posterior parietal cortex (Rossetti, Pisella, & Vighetto, 2003).

#### 74 **2.1.2. Grasping**

75 Grasping corresponds to the shaping of the hand while taking an object (e.g., a paper clip  
76 calls for a precision grip whereas a pencil holder calls for a power grip; e.g., Bongers, Zaal, &  
77 Jeannerod, 2012; Castiello, 2005; Jeannerod, 1986). Graspable tools (in comparison with non-  
78 graspable tools) automatically attract visual attention (e.g., cup versus cactus; Garrido-Vázquez &  
79 Schubö, 2014) and elicit activity in the left premotor and parietal cortex (Grafton, Fadiga, Arbib,  
80 & Rizzolatti, 1997). That being said, the grasping component is in an intermediate position  
81 between reaching and using in that it can be viewed as a high-level perceptual-motor skill  
82 (Rosenbaum, Chapman, Weigelt, Weiss, & Van der Wel, 2012). Indeed, grasping may depend not  
83 only on structural information (i.e., the shape or size of the object; Ellis & Tucker, 2000) but also  
84 on functional information (i.e., knowledge about the function and the prototypical manipulation  
85 of an object; Buxbaum, Kyle, Tang, & Detre, 2006; Jax, Buxbaum, & Moll, 2006) and  
86 intentional/teleological information (i.e., the action to be done with the object; Osiurak et al.,  
87 2008; Rosenbaum et al., 2012). Function-based grasping may depend on the left inferior parietal  
88 lobe whereas structure-based grasping is associated with the left superior parietal lobe  
89 (Buxbaum, Sirigu, Schwartz, & Klatzky, 2003).

#### 90 **2.1.3. Using**

91 Using a tool with an object corresponds to the final step of tool use actions. While both the  
92 reaching and grasping components of action have been observed with similar apparatus in  
93 humans and animals (Rosenbaum et al., 2012), tool use is very specific in humans (see Osiurak,

94 Jarry, & Le Gall, 2010). There is still debate as to the underlying cognitive mechanisms (Buxbaum,  
95 Shapiro, & Coslett, 2015; Osiurak & Le Gall, 2014) but it has been suggested that using a tool with  
96 an object may depend on planning skills (Hartmann, Goldenberg, Daumüller, & Hermsdörfer,  
97 2005), semantic knowledge about tool function and context of use (Osiurak, 2014; Rothi, Ochipa,  
98 & Heilman, 1991; Roy & Square, 1985) and technical reasoning about physical properties of tools  
99 and objects (Osiurak et al., 2010, 2011; for a similar view, see Goldenberg & Hagmann, 1998). For  
100 instance, if one intends to eat a slice of tomato, technical reasoning indicates him/her that a cutting  
101 action and an abrasive tool are needed, semantic knowledge provides information as to where  
102 these properties can be found in near spaces (e.g., a knife has these properties and can be found  
103 in a kitchen; Osiurak & Badets, 2016) and planning is required to organize the whole action  
104 sequence. Planning skills are frequently assessed with the Tower of London test (Shallice, 1982),  
105 in which performance has been associated with bilateral activations in prefrontal cortex and  
106 superior parietal cortex (Newman, Carpenter, Varma, & Just, 2003). Technical reasoning can be  
107 assessed by novel tool use and has been suggested to depend on the left inferior parietal lobe  
108 (Goldenberg, 2009; see also Reynaud, Lesourd, Navarro, & Osiurak, 2016). Semantic memory can  
109 be assessed by picture matching tasks and relies on the activity of the ventral, temporal lobes (e.g.,  
110 Mummery et al., 2000).

## 111 **2.2. DIAGNOSIS AND DISSOCIATIONS IN OPTIC ATAXIA**

112 Lesions in the posterior parietal cortex can result in optic ataxia, that is, inaccurate  
113 movement trajectories when reaching for visual objects. It is a specific visuo-motor disorder  
114 which can be observed despite normal visual and motor functions (Perenin & Vighetto, 1988).  
115 Rossetti, Pisella and Vighetto (2003) reviewed exclusion criteria for the diagnosis of optic ataxia:  
116 (1) the visual field should be spared in the area concerned by the visuomotor deficit; (2)  
117 proprioception should be spared so that the deficit is elicited under visual control only; (3)  
118 intrinsic motor or cerebellar deficits should be ruled out; (4) deficits in visual space perception  
119 may be observed but they should not be sufficient to account for severe misreaching errors.

120 The differential diagnosis between optic ataxia and apraxia (i.e., the inability to perform  
121 voluntary gestures in the absence of sensory or motor deficits; Rothi et al., 1991) is sometimes  
122 difficult. Optic ataxia can be unilateral – following left brain damage (Revol et al., 2003; Perenin &  
123 Vighetto, 1988) – and affects the spatial accuracy of reaching and grasping movements performed  
124 under visual control, following contralateral lesions in the superior parietal lobule and precuneus  
125 (area 7). In contrast, apraxia is generally a bilateral symptom that impairs either tool use or  
126 gestures performed without visual control (e.g., imitation of reflexive configurations), and results  
127 from lesions in the left inferior parietal lobe and parieto-occipital junction (areas 39 and 40;  
128 Goldenberg, 2009).

129 Several dissociating functions have been described in patients with optic ataxia. The latter  
130 is frequently more severe in non-foveal vision (Buxbaum & Coslett, 1997; Garcin, Rondot, & De  
131 Recondo, 1967; Perenin & Vighetto, 1988) but both hand and field effects have been documented  
132 (Perenin & Vighetto, 1988; Revol et al., 2003). Also, optic ataxia has been interpreted as an  
133 impairment of real-time automatic adjustments rather than a complete inability to program  
134 reaching movements (Rossetti et al., 2003; Rossetti, Pisella, & McIntosh, 2017). Classically,  
135 patients with optic ataxia also have grasping deficit in that they demonstrate poorly scaled grip  
136 aperture, yet grasping can be selectively impaired (Jeannerod, Deceti, & Michel, 1994; Sirigu et al.,  
137 1995), suggesting relative independence between the reaching and grasping components of  
138 action. Another famous dissociation is the one between impaired immediate and better delayed  
139 reaching, while healthy participants demonstrate the reverse pattern, especially in peripheral  
140 vision (e.g., Himmelbach & Karnath, 2005; Rossetti et al., 2005). On ground of this paradoxical  
141 delay effect, Himmelbach et al. (2009) suggested that both immediate and delayed reaching  
142 movements may rely on occipitoparietal brain regions.

### 143 **2.3. REHABILITATION OF OPTIC ATAXIA**

144 The literature is sparse on optic ataxia rehabilitation, probably because it is a rare – yet  
145 probably overlooked – deficit (Jacob, Jacob, Albornoz, & Biswas, 2002). The objective of a therapy

146 should be the generalization of what has been learned to a variety of contexts, and the  
147 rehabilitation method should be to provide compensatory strategies allowing patients to correct  
148 their errors (Perez, Tunkel, Lachmann and Nagler, 1996).

149         Previous single case studies suggested that starting 4-to-6 month therapies during the first  
150 year post-stroke with either unspecified outpatient rehabilitation (Moscote-Salazar et al., 2016)  
151 or learning of compensatory strategies, remediation exercises and activities of daily living  
152 (Zgaljardic, Yancy, Levinson, Morales, & Masel, 2011) may be effective in the treatment of Balint's  
153 syndrome (i.e., simultagnosia, ocular apraxia, optic ataxia) – but with no specific effect on reaching  
154 movements. However, it is usually accepted that spontaneous recovery mainly occurs during the  
155 first year following the stroke, therefore it is difficult to disentangle the relative effects of either  
156 spontaneous remission or rehabilitation. Rosselli, Ardila and Beltran (2001) started a 12-month  
157 rehabilitation program – based on visual tracking, convergence and reading exercises, and  
158 activities of daily living – more than a year after the brain embolism. This method led to significant  
159 improvement in tasks involving visual scanning, with probably low influence of spontaneous  
160 recovery, yet there was no available data regarding the specific effect of rehabilitation on reaching  
161 skills. Actually, the specific rehabilitation of reaching movements has received greater attention  
162 in patients with hemiparesis, in whom the study of spontaneous compensations has led to  
163 effective therapies (e.g., restraining trunk movements if the patient relies on the latter to  
164 compensate for upper limb deficits; Thielman, Kaminski, & Gentile, 2008).

165         As can be seen, much remains to be done in this field. To our knowledge, the effect of mere  
166 movement repetition as well as the evolution of spontaneous compensation strategies have not  
167 been studied yet in the field of optic ataxia. Nevertheless, the “movement history effect” has been  
168 described in healthy adults whereby a prior grasping action reduces the planning time of a  
169 subsequent grasping action performed with the same hand (e.g., Valyear & Frey, 2014). Since this  
170 effect is present in healthy adults, it might prove beneficial for patients with optic ataxia. Here, we  
171 present the case of a patient with optic ataxia, who spontaneously set up different compensation

172 methods across time and benefited from a single training session consisting of repetitive reaching  
173 movements.

### 174 **3. CASE REPORT**

175 Figure 1 displays a timeline of the case study. M.B. was a 75 year-old, right-handed  
176 pensioner. His medical history included: Type 2 diabetes, high blood pressure, smoking,  
177 dyslipidemia, chronic renal failure treated by hemodialysis, and sleep apnea syndrome treated by  
178 positive pressure ventilation. In 2001, he sustained a first ischemic stroke which provoked lesions  
179 in the left middle cerebral artery territory. At that time, he recovered with little disability (see  
180 Figure 1). In 2014, M.B. suddenly became confused but he did not present any obvious language,  
181 motor or sensory deficits according to his wife. After three days, he eventually visited the  
182 emergency department. Brain imaging revealed large ischemic lesions in the left occipital,  
183 temporal and parietal lobes (Brodmann areas 18, 19, 21, 22, 37, 39, 40) but also in the cerebellum,  
184 the left caudate nucleus and the right thalamus (Figure 2).

185 At the 3-month follow-up, M.B. had various neuropsychological sequelae that were  
186 consistent with the presence of left parietal lesions, including tool use disorders (Figure 1). He  
187 spontaneously described a disabling reaching deficit with his right hand. For example, when he  
188 tried to reach and grasp his phone, he had to concentrate a lot to initiate the movement, then his  
189 hand wandered twenty centimeters above the phone and/or passed by it. Interestingly, he found  
190 a way to compensate this symptom: If he first reached the target with his left hand, then he could  
191 reach it with his right hand with considerably less hesitation. This strategy was very effective but  
192 also time-consuming, leading him to underutilize his right hand. It was decided to re-assess this  
193 phenomenon during long-term follow-up. M.B. returned home and received weekly speech  
194 therapy. One year later, he did not complain about tool use disorders anymore but his reaching  
195 deficit remained a disabling symptom so we started the following clinical investigation. M.B. gave  
196 his informed consent to this study.

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198 Please insert Figure 1 and Figure 2 about here.

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## 200 **4. CLINICAL INVESTIGATION**

### 201 **4.1. GENERAL TESTING STRATEGY**

202 M.B.'s gestures were investigated in order to answer the following questions: (1) Did the  
203 reaching deficit correspond to optic ataxia? (2) Which components of action were at stake among  
204 reaching, grasping and using? (3) Did reaching time depend on the target object? (4) Which  
205 compensation method was the most effective? (5) Did repetitive testing reduce optic ataxia?

### 206 **4.2. DIAGNOSING OPTIC ATAXIA**

207 **Method.** The aim of this testing session was to clarify the nature of M.B.'s reaching deficit.  
208 To this end, M.B. was tested under three comparable conditions:

209 *Test 1. Reaching (visual input).* M.B. was asked to reach and touch (but not grasp) a wooden  
210 cube (3\*3\*3 cm) with his hand under visual control. Before starting a trial, M.B. was asked to  
211 replace his hand palm-down in a central starting position on the desk, about ten centimeters from  
212 his trunk.

213 *Test 2. Reaching (proprioceptive input).* Proprioceptive pointing may be impaired too in  
214 optic ataxia (Blangero et al., 2007). In order to disentangle the relative contributions of  
215 proprioceptive and visual inputs, M.B. was asked to close his eyes, then to reach the thumb of one  
216 of his hands with the other hand. Before starting a trial, the examiner placed M.B.'s target hand in  
217 the left, central or right visual field so as to make Test 1 and Test 2 comparable.

218 *Test 3. Pointing (visual input).* The purpose of this test was to ascertain that the reaching  
219 deficit was indeed a *reaching* deficit and could not be accounted for by intrinsic visual disorders

220 (e.g., hemianopia). M.B. was given a laser pointer and asked to point at targets presented in the  
221 left, central or right visual field. Targets were located in the reachable, peri-personal space so as  
222 to allow comparison with previous tests. The starting position was M.B.'s trunk so as to ensure  
223 that he stopped pointing at targets between items.

224 In each of these three tests, M.B. underwent the same 18 trials in the same order with either  
225 his left or his right hand (Table 1). The target was located about thirty centimeters from the  
226 starting point in either the left, central or right visual field with a 90-degree angle difference  
227 between each position. When targets were in either the left or right visual field, M.B. was urged to  
228 gaze at a central fixation cross drawn on the desk (which corresponded to the location of the target  
229 cube when it was in the central visual field); if he did not, the item was considered invalid and  
230 repeated. M.B. was instructed to either reach (Tests 1 and 2) or point (Test 3) the target at the  
231 "go" signal, then to come back to the starting position as quickly as possible and so on until the  
232 examiner interrupted the session. The session was filmed and coded afterwards. For each item,  
233 the score was the number of back-and-forth movements between the starting position and the  
234 target, in no more than 10 seconds from the "go" signal.

235 **Results and conclusion.** Results are displayed in Figure 3. M.B.'s reaching deficit was not  
236 caused by somatosensory loss because he performed better in the "proprioceptive" condition than  
237 in the "visual" condition. The left hand/right hand difference was overall more important in Test  
238 1 than in other tests, suggesting that the Hand effect was relatively specific to visually-driven  
239 reaching movements. Subsequently, the reaching deficit was probably not caused by intrinsic  
240 motor deficits because in that case, the Hand effect should have been constant across conditions.  
241 M.B. also demonstrated a field effect (i.e., severe misreaching in the right visual field) already  
242 documented in patients with optic ataxia (e.g., G.H.; Himmelbach & Karnath, 2005). Although this  
243 finding can be explained by right hemianopia in the case of M.B., errors were also frequent in the  
244 central visual field. On this ground, it seemed reasonable to conclude that M.B.'s reaching deficit  
245 with the right hand was the consequence of optic ataxia, at least in the left and central visual fields.

246 This conclusion was also consistent with M.B.'s spontaneous complaints about his reaching skills  
247 as the latter is not typical of mere hemianopia.

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249 Please insert Table 1 and Figure 3 about here.

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### 251 **4.3. REACHING, GRASPING AND USING COMPONENTS OF ACTION**

252 **Method.** This testing session was designed to assess each component of action separately:  
253 Reaching, grasping and using. The latter component was divided into planning skills, semantic  
254 memory and technical reasoning which are good predictors of tool use skills in daily life (see  
255 Section 2.1).

256 *Test 4. Reach-to-grasp (reaching).* M.B. was asked to reach and grasp six different objects  
257 presented in his central visual field with his right hand (Table 1). Objects were removed and  
258 reinstalled between trials. The starting and ending positions were the same as in previous tests.  
259 Reaching time was measured with a stopwatch as the time taken to reach and touch the object,  
260 from a "go" signal to the hand/object contact.

261 *Test 5. Reach-to-grasp (grasping).* Tests 4 and 5 were actually one and the same testing  
262 session but it was coded twice in different ways based on video recordings. For each item, grip  
263 scale aperture was coded when the hand moved within ten centimeters of the object. The grasping  
264 component was considered normal and one point was given if grip aperture (i.e., the space  
265 between the thumb and the forefinger) fitted the size of the object: A precision grip (i.e., the object  
266 is grasped between the thumb, the forefinger and the middle finger) was expected for small  
267 objects (i.e., coin, paper clip) and medium objects (i.e., lighter, inhaler), whereas a power grip (i.e.,  
268 the object is grasped with all the fingers) was expected for larger objects (i.e., pencil holder, large  
269 wooden cube; Table 1). Excessive anticipation or grip aperture as well as late corrections were  
270 worth 0 point. There were 18 items so the maximum score was 18.

271            *Test 6. Tower of London.* This test assessed planning skills and consisted in a modified,  
272 shorter version of the classical Tower of London test (Jarry et al., 2013). In each item, M.B. was  
273 given 2 minutes to replicate a configuration of three colored beads arranged on three vertical  
274 sticks (short, medium, long). He was instructed to move only one bead at a time on the sticks, and  
275 to do as few moves as possible but he could use both hands. He had to solve six problems of  
276 increasing difficulty (i.e., two to seven moves). Performance was rated on a 3-point scale  
277 depending on the number of moves (maximum score = 18).

278            *Test 7. Picture matching.* The use of familiar tools calls for semantic knowledge about their  
279 function and context of use (Osiurak, 2014; Roy & Square, 1985). This component was assessed  
280 by asking M.B. to select among four pictures the one that matched the picture of a tool. Pictures  
281 could be matched on either a functional criterion (e.g., target = match; choice = *lighter*, pen, coffee  
282 maker, colander) or a contextual criterion (e.g., target = match; choice = *anniversary*, wedding,  
283 Christmas day, baptism) depending on items. There were ten items in each condition (plus two  
284 corrected, practice items). Each correct answer given within 20 seconds was worth 1 point  
285 (maximum score = 20).

286            *Test 8. Mechanical Problem Solving.* The final step of tool use actions is the interaction  
287 between the tool and the object, which may depend on technical reasoning about mechanical  
288 properties of both (Osiurak et al., 2010). Technical reasoning can be assessed using mechanical  
289 problem-solving tasks in which patients have to select and use tools for which there is no pre-  
290 existing usage (e.g., choosing a tool to lever a cylinder; Goldenberg & Hagmann, 1998). Here, M.B.  
291 was presented successively with three mechanical problem-solving tasks previously described by  
292 Lesourd et al. (2015) and Baumard et al. (2016, 2017; Supplementary Figure 1). He was asked to  
293 extract a red wooden cube out from a transparent box, using both hands and one or more tools to  
294 be selected among eight rods offering different mechanical properties (e.g., long/short,  
295 rigid/bendable). The time limit was set to 3 minutes per item and performance was scored on a  
296 3-point scale: (3) The cube is extracted from the box; (2) The first step of the problem is

297 completed; (1) The cube has been reached with a rod but the first step is not completed; (0) The  
298 participant does not reach the cube. The maximum total score was 9 (i.e., 3 problems x 3 points).

299 **Results and conclusion.** Reaching movements were very slow and inaccurate whereas  
300 grasping was relatively spared (Table 2). In parallel, planning skills, semantic knowledge and  
301 technical reasoning were spared. This is consistent with clinical observation that in 2015, M.B. no  
302 longer reported tool use disorders. With regard to the distinction between reaching, grasping and  
303 using (Section 2.1), M.B.'s core symptom was the inability to initiate and guide fast reaching  
304 movements under visual control.

305 -----

306 Please insert Table 2 about here.

307 -----

#### 308 ***4.4. RELATIONSHIP BETWEEN REACHING TIME AND OBJECT IDENTITY***

309 **Method.** In order to determine whether characteristics of the object had an influence on  
310 reaching skills, performance in Test 4 was recoded with different criteria.

311 *Test 9. Reach-to-grasp.* This testing session was the same as Test 4 and Test 5 but it was  
312 coded – and named – differently. The sequence of items was important: In some cases, the same  
313 object was presented twice in a row whereas in other cases, the object was replaced by a new one  
314 of different shape or size. (Table 1). Objects were always presented in the central visual field. The  
315 measure was the time taken to reach and touch the object.

316 **Results and conclusion.** As shown in Figure 4, M.B.'s reaching performance improved  
317 when he was presented consecutively with the same object but decreased when he was presented  
318 with a new one. This was the case even though object size and the expected grip remained  
319 unchanged. So, it was concluded that reaching skills were influenced by mere object substitution.

320 -----

321 Please insert Figure 4 about here.

322 -----

323 **4.5. COMPARISON OF TWO COMPENSATION METHODS**

324 **Method.** M.B. spontaneously set up compensation methods that evolved between the post-  
325 acute phase and the long-term follow-up consultation. Three months after the stroke, his method  
326 was to first reach objects with the left hand, then with the right hand. Clinically, this method  
327 appeared to be efficient. One year later, he did not engage in such behavior anymore. Instead, he  
328 grasped his right hand with his left hand so as to correct the movement trajectory of the right  
329 hand. From there, he became able to reach objects with his right hand only, but only for a few  
330 seconds, after which he had to start compensating again. Based on this clinical observation it was  
331 decided to test the effectiveness of the two aforementioned compensation methods.

332 *Test 10. Unimanual compensation.* As in Test 1, M.B. was asked to reach and touch a wooden  
333 cube which was placed either in the left, central or right visual field. There were six blocks of three  
334 items (Table 1). In the first item, M.B. was asked to reach the target only with his right hand. In  
335 the second item, he was asked to do the same but with his left hand. The third item was the same  
336 as the first one. The position of the target remained identical across the three items. There was no  
337 delay between the three items of a series but a pause of ten seconds between each series of items,  
338 during which M.B. let his hand rest at the starting position. The measure was the number of back-  
339 and-forth reaching movements in 10 seconds.

340 *Test 11. Bimanual compensation.* This test was very similar to Test 10 except that during  
341 item 2, M.B. was asked to use his second compensation method, that is, reaching the target with  
342 his right hand while holding the latter with his left hand so as to correct the movement trajectory  
343 – of his right hand.

344 **Results and conclusion.** As shown in Figure 5, the bimanual compensation method was  
345 more effective than the unimanual compensation method at the time of testing. For all that, none

346 of the methods was more effective than the mere repetition of reaching movements (Test 1).  
347 Likewise, repeating items in Test 4 was very helpful for M.B. (Figure 4). As a consequence, these  
348 results are interpreted in terms of repetition effect rather than compensation effect. M.B.'s  
349 reaching performance improved only if he successfully reached the target at least once with his  
350 right hand before subsequent tries.

351 -----

352 Please insert Figure 5 about here.

353 -----

#### 354 ***4.6. TRAINING EFFECT***

355 **Method.** We met M.B. on June 13, 2014, then on December 17, 2015. He passed Tests 1 to  
356 11 on January 8, 2016. On this occasion, after about one hour and a half of continuous testing,  
357 M.B.'s reaching performance slightly improved. After the lunch break, he spontaneously reported  
358 that using his right hand was easier, which became obvious after a few tries. Therefore, it was  
359 decided to compare different testing sessions performed with the right hand in the central visual  
360 field: (1) Test 1 (i.e., reaching a cube under visual control) had been conducted at 10 AM; (2) Test  
361 4 (i.e., reaching different objects under visual control) had been administered at 11:30 AM; (3)  
362 Test 4 was renewed at 6 PM, after various reaching tasks that were not described in this study;  
363 (4) Four new objects (i.e., stopwatch, pencil, glass, jug) were presented once each at 6 PM so as to  
364 determine whether improvement was object-dependent; (5) Test 4 was proposed again on June  
365 3, 2016 to verify whether improvement was sustainable. At that time reaching was tested with his  
366 left hand too as a point of comparison; (6) On this occasion, we also repeated imitation of  
367 meaningless gestures in order to compare the effects of training on optic ataxia and apraxia and,  
368 on that basis, determine how specific was the improvement of reaching skills.

369 *Test 12. Imitation of meaningless gestures.* M.B. was asked to imitate ten reflexive hand  
370 configurations with each hand, "like in a mirror", without delay (Goldenberg, Münsinger, &

371 Karnath, 2009). Performance was scored on a 2-point scale: (2) correct imitation within the time  
372 limit (i.e., 10 seconds); (1) approximate imitation in less than 5 seconds or correct imitation in  
373 more than 5 seconds; (0) incorrect imitation. Scoring considered only the final position of the hand  
374 relative to the body. The maximum score was 20.

375 **Results and conclusion.** Figure 6 shows a training effect for optic ataxia since the reaching  
376 performance improved across testing sessions, especially in the afternoon. Tests 1 to 9 were  
377 performed in the morning and hence this training effect was presumably low at that time. Besides,  
378 this effect was neither object-dependent – since generalization was observed with new objects –  
379 nor context-dependent – since the third training session (i.e., at 6 PM) took place in M.B.’s room  
380 rather than in the office. Likewise, the spatial location of the target relative to the body did not  
381 modify the reaching behavior: As long as M.B. was allowed to gaze at objects, he was able to grasp  
382 tools on both the left and the right sides. Actually, while leaving the unit M.B. demonstrated to  
383 caregivers how easy it was for him to grasp any object he found. This improvement persisted five  
384 months later although M.B. did not receive rehabilitation services during this period. On this  
385 occasion the repetition of imitation tasks did not induce a similar improvement, suggesting that  
386 repetitive training is efficient in the treatment of optic ataxia but not apraxia.

387 -----

388 Please insert Figure 6 about here.

389 -----

## 390 **5. GENERAL DISCUSSION**

### 391 **5.1. MAIN RESULTS**

392 Optic ataxia was diagnosed in M.B. because he demonstrated severe reaching errors under  
393 visual control in both foveal and peripheral vision, which could not be accounted for by  
394 hemianopia, proprioceptive loss or intrinsic motor deficit (see criteria in Rossetti et al., 2003;

395 Rossetti & Pisella, 2018). Subsequent clinical studies demonstrated (1) a classical dissociation  
396 between reaching and grasping; (2) changes in reaching time after mere object substitution; (3)  
397 the efficacy of spontaneous compensation methods and mere movement repetition; (4) a clear-  
398 cut improvement of reaching skills after an intensive one-day repetitive training session. Each of  
399 these findings may shed light on both the pathological characteristics of reaching and grasping  
400 actions, and potential rehabilitation strategies for optic ataxia.

## 401 **5.2. PATHOLOGICAL CHARACTERISTICS OF OPTIC ATAXIA**

### 402 **5.2.1. Reaching versus grasping**

403 Even though the coding system used to test the grasping component probably lacked  
404 sensitivity (i.e., correct/incorrect grasping based on video recordings), the first finding here is the  
405 dissociation between severely impaired reaching and relatively spared grasping – which  
406 corresponded to M.B.'s complaints. Presumably, M.B.'s grasping was slightly impaired as a  
407 secondary consequence of inaccurate reaching movements (Cavina-Pratesi, Ietswaart,  
408 Humphreys, Lestou, & Milner, 2010). The reverse dissociation – i.e., impaired grasping but spared  
409 reaching – has already been documented (e.g., Binkofski et al., 1998; Jeannerod et al., 1994; Sirigu  
410 et al., 1995). This is consistent with neuroimaging data demonstrating that grasping may call for  
411 a dorsolateral circuit (i.e., from the anterior intraparietal sulcus to the ventral premotor cortex)  
412 whereas reaching may rely on a dorsomedial circuit (i.e., from the parieto-occipital transition zone  
413 to the dorsal premotor cortex; Vingerhoets, 2014). With regard to this functional organization,  
414 M.B.'s lesions in the occipito-parietal regions (Figure 2) may explain the relatively isolated  
415 reaching deficit.

416 Beyond dissociations between brain regions, why was grasping better than reaching? One  
417 way of answering this question is to look at the parameters that modulate reaching and grasping.  
418 As regards reaching, demands in movement trajectory remain constant as long as the starting  
419 position of the hand and the end position of the object are fixed. The subsequent goal of the action  
420 once the object has been grasped, has only late influence on timing parameters (i.e., deceleration;

421 Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987) and spatial parameters (i.e., end-  
422 point; Ambron, Lingnau, Lunardelli, Pesavento and Rumiati, 2015). In contrast, grip selection and  
423 scaling is much more dependent on the subsequent task (e.g., grabbing a spoon with full hands to  
424 dig in dry land versus holding it with three fingers to eat soup). Neurons in area F5 – which are  
425 thought to underlie grasping (Himmelbach & Karnath, 2005) – discharge in relation with goal-  
426 directed actions (Rizzolatti, Fogassi, & Gallese, 2001). From this point of view, grasping may be  
427 only the motor product of higher-level cognitive processes (Ambron et al., 2015; Jeannerod 1986;  
428 Rosenbaum et al., 2012) and thus could be considered the “least motoric” of motor behaviors in  
429 the sense that the way we grasp tools may emerge on ground of any mechanism providing  
430 teleological information (see also Cisek, 2007). Besides object shape (Ellis & Tucker, 2000), task  
431 goal (Osiurak et al., 2008; Randerath, Li, Goldenberg, & Hermsdörfer, 2009) and precision  
432 demands (Rosenbaum et al., 2012), technical reasoning and semantic knowledge may also play a  
433 role by informing individuals on potential mechanical actions (e.g., a stone shall be grasped with  
434 a power grip in order to break a window but with a precision grip in order to write in the sand;  
435 Osiurak, 2014) and canonical actions leading to functional grasps (e.g., even an oversized pencil  
436 shall be grasped with the first three fingers because it corresponds to the way it is usually grasped,  
437 for writing; Buxbaum et al., 2006; Jax & Buxbaum, 2013). Overall, the common point between  
438 these sources of information is that they provide teleological information about which actions to  
439 perform and how, which in return allows grip selection (Cisek, 2007). This “teleological” approach  
440 completes the classical dichotomy (see Binkofski & Buxbaum, 2012) between structural grasps –  
441 based on objects’ structure – and functional grasps – based on object semantics – by extending the  
442 range of cognitive mechanisms potentially involved in affordance perception/selection and  
443 grasping. In all likelihood, M.B. was able to access teleological information since he performed  
444 mechanical problem solving and matching tasks in normal range. Subsequently, grasping was  
445 relatively spared. Conversely, it can be assumed that M.B.’s reaching deficit was not the  
446 consequence of a teleological deficit (i.e., the inability to identify the end and means of actions).  
447 Future works on optic ataxia may focus on the relationships between reaching, grasping and

448 different sources of teleological information, especially since recent experimental studies of  
449 healthy adults emphasized the influence of the abstract intention to use an object (i.e., distal,  
450 contextual goals rather than proximal hand-object interactions) on the prior reach-to-grasp action  
451 (Bub, Masson, & van Mook, 2018).

### 452 **5.2.2. Interpreting the substitution effect**

453 M.B.'s reaching performance improved after two presentations of the same object, but  
454 decreased if the second object was different from the first one. So, it can be concluded that object  
455 substitution had an impact on the reaching component of action (i.e., the substitution effect). A  
456 similar object substitution effect has already been demonstrated on grasping in patient I.G.  
457 (Milner et al., 2001). Since object location was fixed, the question arises whether this effect was  
458 provoked either by object substitution *per se* or by repetitive reaching toward the same  
459 localization in peripersonal space.

460 Previous works documented the paradoxical delay effect (e.g., Himmelbach & Karnath,  
461 2005): Introducing a delay between the presentation of the stimulus and the initiation of the  
462 reaching movement increases the reaching time in healthy subjects but decreases it in patients  
463 diagnosed with optic ataxia. In our design, items were necessarily separated by short 3-second  
464 delays (i.e., the time for the examiner to remove the object and place the next one), a delay that is  
465 sufficient to observe substantial improvement of reaching movements (Himmelbach & Karnath,  
466 2005). On this ground, one could assume that the first presentation of the object called for  
467 immediate reaching whereas the second presentation additionally elicited delayed reaching  
468 based on short-term representation of the spatial location of the target. In a sense, M.B. used a  
469 memory-based route to bypass his visuomotor deficit, as did I.G. for grasping (Milner et al., 2001).

470 However, this explanation is not sufficient in itself because it is based on the assumption  
471 that object location, rather than object identity, is stored and reused in delayed reaching. Since  
472 object location was fixed – in the central visual field – the paradoxical delay effect should have led  
473 to progressive improvement across trials independently of object identity, yet this was not

474 observed. Interestingly, Rossetti et al. (2003) suggested that optic ataxia is not due to a general  
475 impairment of visuomotor transformations but distinguished between intentional movement  
476 programming and real-time automatic adjustments (Pisella et al. 2000), with only the latter being  
477 dependent on the superior parietal lobes. Patients with lesions in the parietal lobes and optic  
478 ataxia are able to program movements and reach targets, but they need an unusual amount of time  
479 to adapt to target displacement as if they were acting in the past (Milner et al. 2001). The reverse  
480 pattern (i.e., involuntary object-hand magnetization without intentional programming) has  
481 already been documented in patients with anarchic hand syndrome following lesions of the  
482 corpus callosum and/or of the medial frontal cortex (Della Sala, Marchetti, & Spinnler, 1991;  
483 Osiurak & Badets, 2016). Electrical stimulation of premotor areas also induces involuntary yet  
484 complex motor behaviors (Desmurget et al., 2009; Luria, 1966). These data fit well with a  
485 dissociation between automatic reaching supported by the parietal dorsomedial region  
486 (Vingerhoets, 2014) and voluntary motor programming supported by premotor regions as well  
487 as the inferior parietal region (e.g., Mattingley, Husain, Rorden, Kennard, & Driver, 1998).

488 In this framework, M.B.'s reaching deficit can be understood as a deficit in automatic  
489 movement correction, contrasting with spared intentional programming. In support of this  
490 hypothesis, M.B. obviously made conscious efforts to reach the targets, suggesting he could not  
491 rely on automatic "object-hand magnetization" and hence had to constantly reset intentional  
492 movement programming at each target change. In contrast, the reaching time decreased when the  
493 identity of the target remained unchanged because it was not necessary to initiate new movement  
494 programming. This interpretation may suggest that not only object localization but also object  
495 identity, is integrated into movement programming in proximal-to-distal reach-to-grasp tasks.  
496 The specific influence of object identity – already demonstrated on grip selection (Dixon, McAnsh,  
497 & Read, 2012) – is plausible regarding fMRI findings that changes in either object identity or  
498 orientation elicit more activation in the temporo-occipital and parieto-occipital cortex,  
499 respectively (Valyear, Culham, Sharif, Westwood, & Goodale, 2006). It is also consistent with  
500 previous works demonstrating better grasping skills with familiar than with neutral objects

501 (Jeannerod et al., 1994) – even though it should be noted that what we call “object identity” here  
502 does not necessarily refer to object familiarity or semantics but rather to the mere fact that the  
503 object remains the same across items. To sum up, the substitution effect can be reasonably  
504 interpreted as a consequence of two combined effects caused by occipito-parietal lesions, i.e., the  
505 immediate/delayed dissociation and the voluntary/automatic dissociation.

506         Alternatively, the repetition/substitution effects observed in M.B. may be well explained by  
507 – and actually correspond to - the movement history effect described by Valyear and Frey (2014).  
508 The latter effect is characterized by a reduction of movement time across successive reach-to-  
509 grasp actions performed with the same hand. A critical issue in this field is to determine whether  
510 this improvement depends on characteristics of either the stimulus or the motor output. This issue  
511 was addressed by Randerath, Valyear, Hood and Frey (2015) who observed an effect of both  
512 dimensions and hence concluded that “*instead of attributing it to single aspects, repetition priming-*  
513 *effects are more likely predominantly induced by the facilitation of action selection through*  
514 *reactivation of stimulus bound action units*” (pp. 10). The observation of both a repetition effect  
515 and a substitution effect in M.B.’s case fits well with this hypothesis: Presenting the same object  
516 twice in a row (i.e., same stimulus) at the same location of peripersonal space (i.e., same reaching  
517 movement) may have reinforced abnormally slow stimulus-action binding process whereas  
518 presenting different objects broke this bond and forced M.B. to start programming movements *de*  
519 *novo*. The movement history effect mostly studied in healthy adults seems to be relevant to  
520 understanding some clinical manifestations of optic ataxia. Future works may try to disentangle  
521 the impact of the abovementioned variables on reaching skills and movement training in patients  
522 with optic ataxia.

### 523         **5.3. POTENTIAL IMPLICATIONS FOR OPTIC ATAXIA REHABILITATION**

#### 524         **5.3.1. Interpreting the compensation effect**

525         From the post-acute phase of stroke to the last follow-up consultation, M.B. demonstrated  
526 great adaptive resources. His first compensation method was to reach objects with his left hand,

527 which improved subsequent reaching with the right hand. The paradoxical delay effect (see  
528 Section 5.2.1) may account for this pattern yet another explanation is plausible. Previous studies  
529 have found that unilateral brain activation tends to elicit activations in similar contralateral brain  
530 regions (Belin, Faure, & Mayer, 2008). This may explain some cases of allochiria (i.e., erroneous  
531 localization of sensitive stimuli in the contralateral, non stimulated side of the body; Lhermitte,  
532 1939). So, perhaps visuo-motor connections in the right hemisphere elicited mirror activations in  
533 the left hemisphere, hence facilitating partial spontaneous recovery. In broad terms, M.B. may  
534 have intuitively set up his own brain stimulation therapy, which has already been found to be  
535 effective in post-stroke motor recovery (Lindenberg, Renga, Zhu, Nair, & Schlaug, 2010).

536         Although this first method appeared to be effective at the three-month follow-up, it was no  
537 longer the case at the one-year follow-up. At that time, M.B.'s second compensation method was  
538 to hold and guide his right hand with his left hand, which again improved subsequent reaching  
539 with the right hand. This evolution may reflect either brain reorganization during the recovery  
540 process, M.B.'s trial-and-error strategy toward a more effective compensation method, or both. In  
541 fact, the mere repetition of reaching movements pointed to the same results as this second  
542 compensation method whereas the first method was no longer efficient (Figure 5). So, the key for  
543 subsequent improvement was not delay in itself – as would predict the paradoxical delay effect  
544 (section 5.2.2) – but rather the experience of successfully reaching the target. It amounts to  
545 considering that in M.B.'s case, both trial-and-error learning (no compensation) and errorless  
546 learning (driving his right hand with his left hand) of movement trajectory were efficient. Perhaps  
547 M.B. unconsciously preferred the compensation strategy because it was a faster and less effortful  
548 way to attain the same result.

549         If a first successful reaching movement provided additional information useful for  
550 subsequent reaching movements, the question arises as to what information was gained across  
551 trials. In partial contradiction with the previous paragraph, it is also possible that repetition and  
552 compensation led to similar quantitative improvements (Figure 5) but on the basis of different

553 qualitative information. With regard to compensation, a “somesthetic” hypothesis would be that  
554 left and right hand contact (when holding the right hand with the left hand) provided enhanced  
555 tactile and proprioceptive input, turning the expected visuo-motor reaching movement into a  
556 “somesthetic-motor” movement. For instance, both the left and right elbow angles may have  
557 helped M.B. recoding the position of his right hand relative to the object. In other words, the  
558 reaching movement performed with the right hand under control of the left hemisphere may have  
559 been programmed based on somesthetic information processed in the right hemisphere. With  
560 regard to mere repetition, another “tactile” hypothesis would be that touching the object just once  
561 provided enriched information about its structure that vision could not provide, thus enhancing  
562 affordance perception and the subsequent programming of the reaching movement. If this is  
563 correct, then touching the object should be more critical than reaching it. Even though the training  
564 effect did not allow us to disentangle these hypotheses, we hope this will be of interest to set up  
565 future research on optic ataxia assessment and rehabilitation.

### 566 **5.3.2. Interpreting the training effect**

567 M.B.’s reaching behavior greatly improved after a few hours of training. Before that, optic  
568 ataxia had remained a disabling symptom for almost two years post-stroke – whereas tool use  
569 disorders had spontaneously recovered in December 2015. Spontaneous recovery generally  
570 occurs within three to six months after the injury (Kertesz, 1979) while rehabilitation may be  
571 efficient even if started more than a year after the acute phase (Prigatano, 1999). Therefore, the  
572 evolution from impaired to subnormal reaching performance – on a single day – is interpreted as  
573 a consequence of training rather than spontaneous recovery. This finding suggests that significant  
574 improvement of reaching skills can be obtained even after the typical period of spontaneous  
575 remission.

576 This finding raises a crucial issue: Which underlying process has been trained? It is unlikely  
577 that M.B. learned object locations – as would predict the paradoxical delay effect – because at the  
578 end of the day he was able to reach any object toward any location in its peripersonal space and

579 in different contexts (i.e., office, room). The delay effect might explain successive improvements  
580 across items but not the generalization of this improvement to other objects and spatial locations.  
581 With regard to the dichotomy between automatic reaching and intentional programming (section  
582 5.2.1), another possibility would be that the repetition of reaching movements reinforced  
583 movement programming, thus allowing M.B. to compensate for the loss of automatic reaching  
584 mechanisms. Again, this is unlikely because reaching movements were very fast and totally  
585 effortless at the end of the day. In the framework of the movement history effect (Randerath et al.,  
586 2015) – according to which both the repetition of the stimulus and that of motor coordinates lead  
587 to a decrease in movement time – the training effect may have been induced by the repetition of  
588 motor outputs. Indeed, the facilitation of action selection by movement repetition has been  
589 explained by the reactivation of stimulus-action units. However, M.B. became able to reach objects  
590 for which he had received no training, meaning that he improved with untrained stimuli. This  
591 amounts to considering that training was due to the repetition of motor outputs themselves (i.e.,  
592 the coordinates of reaching movements in the peripersonal space), yet in that case one may  
593 wonder why optic ataxia did not recover spontaneously for M.B. had to reach and grasp objects  
594 every day. Therefore, the observed decrease in reaching time may rather suggest that automatic  
595 visuo-motor conversion mechanisms recovered to subnormal levels. In line with the previously  
596 mentioned automatic/intentional dichotomy (Pisella et al., 2000; Rossetti et al., 2003), it is  
597 proposed that objects elicited automatic object-hand magnetization in a more effective way after  
598 intensive training sessions. This contrast between controlled, effortful reaching before training  
599 and effortless reaching after training suggests that under normal conditions, a balance between  
600 intentional programming and automatic reaching allows individuals to reach tools without having  
601 to focus on their movement, thereby freeing attentional resources for tool use.

602 In contrast with optic ataxia, repetitive training had only little impact on visuo-imitative  
603 apraxia. Previous studies demonstrated that three training sessions per week with enriched  
604 feedback (i.e., verbal facilitations, demonstration of the correct gesture, passive positioning of the  
605 hand) did not allow significant improvement in imitation tasks (Smania, Girardi, Domenicali, Lora

606 and Aglioti, 2000). This differential effect of training on optic ataxia and apraxia may reflect the  
607 fact that optic ataxia is a deficit in automatic visuo-motor conversion mechanisms (Rossetti et al.,  
608 2003) while imitation of meaningless gestures is thought to rely on "higher-level" cognitive  
609 mechanisms (e.g., body knowledge, categorical apprehension of body parts; Goldenberg, 1995,  
610 2009). Based on this distinction and M.B.'s results, it is proposed that rehabilitation of apraxia  
611 might call for complex compensation strategies – requiring the identification of specific  
612 underlying impairments (see Cantagallo, Maini, & Rumiati, 2012; Rossetti, Rode, & Goldenberg,  
613 2005) – whereas reaching behaviors that we share with animals can be trained through repetitive  
614 training in some instances.

## 615 **6. CONCLUSION**

616 To conclude, M.B.'s case provides insight into both the pathological characteristics of optic  
617 ataxia, and potential rehabilitation methods. As regards the former, integrating literature on optic  
618 ataxia (i.e., reaching, grasping) and apraxia (i.e., using) may enrich our understanding of motor-  
619 like deficits (Ambron et al., 2015). In this regard, the substitution effect observed in M.B. suggests  
620 that object identity is one of the multiple variables that affect the programming of reaching  
621 movements: In some patients, repeatedly reaching toward the same object may improve the  
622 reaching performance. Studying M.B.'s spontaneous compensation strategies allowed us to  
623 ascertain that the mere repetition of reaching movements had a positive effect, to the point M.B.  
624 almost recovered to normal level. M.B.'s case seems to provide one of the first examples of optic  
625 ataxia rehabilitation, which is of particular interest in the light of famous patients extensively  
626 explored and tested in the laboratory over decades: AT and IG (Pisella et al. 2000; Rossetti et al.  
627 2005), DF (Rossetti et al., 2017), U.S. and G.H. (Himmelbach & Karnath, 2005). These findings  
628 imply that optic ataxia can be trained by repetitive training even two years post-stroke – and  
629 despite the presence of visuo-imitative apraxia. They might also encourage therapists to propose  
630 intensive training sessions –throughout an entire day when possible – instead of short treatment

631 sessions several days apart. In terms of strategies, restoring automatic object-hand  
632 automatization through repetitive training may be a relevant therapeutic goal in the treatment of  
633 optic ataxia.

634         As a limit, the lack of substantial normative data in the present work makes it difficult to  
635 ascertain the normality of some performances – hence within-patient comparisons are more  
636 compelling. It can also be mentioned that M.B.'s reaching performance improved toward objects  
637 presented in the central visual field, yet reaching in peripheral vision – a classical characteristic  
638 of optic ataxia – may still be impaired. So, despite tangible benefits for M.B.'s daily life it cannot be  
639 concluded that training cured optic ataxia in itself. Besides, it is unlikely that training leads to such  
640 clear-cut improvement in all patients. The absence of severe aphasia or other higher-order  
641 cognitive impairments (i.e., technical reasoning, semantic memory, planning) was probably a  
642 facilitating factor. It should also be noticed that previous cases of optic ataxia were tested in the  
643 first days post-stroke (e.g., patients U.S. and G.H.; Himmelbach & Karnath, 2005) whereas M.B. was  
644 tested more than a year after his stroke. Aside from intrinsic individual differences in brain and  
645 psychological organization, functional inhibition (i.e., diaschisis) in the acute phase, and functional  
646 reorganization in long-term follow-up, are likely to result in different clinical presentations and  
647 might explain the – atypical – training effect presented here.

648

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## **DISCLOSURE STATEMENT**

657

The authors report no conflicts of interest.

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## REFERENCES

- 660 Ambron, E., Lingnau, A., Lunardelli, A., Pesavento, V., & Rumiati, R.I. (2015). The effect of  
661 goals and vision on movements: A case study of optic ataxia and limb apraxia. *Brain and*  
662 *Cognition*, 95, 77-89. doi: 10.1016/j.bandc.2015.01.006
- 663 Baumard, J., Lesourd, M., Jarry, C., Merck, C., Etcharry-Bouyx, F., Chauviré, V., ... & Le  
664 Gall, D. (2016). Tool use disorders in neurodegenerative diseases. Roles of semantic  
665 memory and technical reasoning. *Cortex*, 82, 119-132. doi: 10.1016/j.cortex.2016.06.007
- 666 Baumard, J., Lesourd, M., Remigereau, C., Jarry, C., Etcharry-Bouyx, F., Chauviré, V., ... &  
667 Le Gall, D. (2017). Tool use in neurodegenerative diseases: Planning or technical  
668 reasoning? *Journal of Neuropsychology*. doi: 10.1111/jnp.12121
- 669 Belin, C., Faure, S., & Mayer, E. (2008). Hemispheric specialization versus inter-hemispheric  
670 communication. *Revue Neurologique*, 164, S148-153. doi: 10.1016/S0035-  
671 3787(08)73306-X
- 672 Binkofski, F., & Bubbaum, L.J.G. (2012). Two action systems in the human brain. *Brain and*  
673 *Language*, 127(2), 222-229. doi: 10.1016/j.bandl.2012.07.007
- 674 Binkofski, F., Dohle, C., Posse, S., Stephan, K.M., Hefter, H., Seitz, R.J., & Freund, H.J.  
675 (1998). Human anterior intraparietal area subserves prehension: A combined lesion and  
676 functional MRI activation study. *Neurology*, 50(5), 1253-1259.
- 677 Blangero, A., Ota, H., Delporte, L., Revol, P., Vindras, P., Rode, G., ... & Pisella, L. (2007).  
678 Optic ataxia is not only 'optic': Impaired spatial integration of proprioceptive information.  
679 *NeuroImage*, 36, T61-T68. doi: 0.1016/j.neuroimage.2007.03.039
- 680 Bongers, R.M., Zaal, F.T.J.M., Jeannerod, M. (2012). Hand aperture patterns in prehension.  
681 *Human Movement Science*, 31, 487-501. doi: 10.1016/j.humov.2011.07.014

- 682 Bub, D.N., Masson, M.E.J., & van Mook, H. (2018). Switching between lift and use actions.  
683 *Cognition*, 174, 28-36. doi: 10.1016/j.cognition.2018.01.013
- 684 Buxbaum, L.J., & Coslett, H. (1997). Subtypes of optic ataxia: Reframing the disconnection  
685 account. *Neurocase*, 3(3), 159-166. doi: 10.1080/13554799708404050
- 686 Buxbaum, L.J., Kyle, K.M., Tang, K., & Detre, J.A. (2006). Neural substrates of knowledge of  
687 hand postures for object grasping and functional object use: Evidence from fMRI. *Brain*  
688 *Research*, 1117(1), 175-185. doi: 10.1016/j.brainres.2006.08.010
- 689 Buxbaum, L.J., Shapiro, A.D., & Coslett, H.B. (2015). Reply: Apraxia: A gestural or a cognitive  
690 disorder? *Brain*, 138(3), e334. doi: 10.1093/brain/awu240
- 691 Buxbaum, L.J., Sirigu, A., Schwartz, M.F., & Klatzky, R. (2003). Cognitive representations of  
692 hand posture in ideomotor apraxia. *Neuropsychologia*, 41(8), 1091-1113. Retrieved from  
693 <https://www.ncbi.nlm.nih.gov/pubmed/12667544/>
- 694 Cantagallo, A., Maini, M., & Rumiati, R.I. (2012). The cognitive rehabilitation of limb apraxia  
695 in patients with stroke. *Neuropsychological Rehabilitation*, 22(3), 473-488. doi:  
696 10.1080/09602011.2012.658317
- 697 Castiello, U. (2005). The neuroscience of grasping. *Nature Reviews Neuroscience*, 6, 726-736.  
698 doi: 10.1038/nrn1744
- 699 Cavina-Pratesi, C., Iestwaart, M., Humphreys, G.W., Lestou, V., & Milner, A.D. (2010).  
700 Impaired grasping in a patient with optic ataxia: Primary visuomotor deficit or secondary  
701 consequence of misreaching? *Neuropsychologia*, 48(1), 226-234. doi:  
702 10.1016/j.neuropsychologia.2009.09.008
- 703 Cisek, P. (2007). Cortical mechanisms of action selection: The affordance competition  
704 hypothesis. *Philosophical Transactions of the Royal Society B*, 362, 1585-1599. doi:  
705 10.1098/rstb.2007.2054

- 706 Crawford, J. R., & Garthwaite, P. H. (2002). Investigation of the single case in  
707 neuropsychology: Confidence limits on the abnormality of tests scores and test scores  
708 differences. *Neuropsychologia*, 40, 1196–1208. [https://doi.org/10.1016/S0028-](https://doi.org/10.1016/S0028-3932(01)00224-X)  
709 3932(01)00224-X
- 710 Della Sala, S., Marchetti, C., Spinnler, H. (1991). Right-sided anarchic (alien) hand: A  
711 longitudinal study. *Neuropsychologia*, 29(11), 1113-1127.
- 712 Desmurget, M., Reilly, K.T., Richard, N., Szathmari, A., Mottolese, C., & Sirigu, A. (2009).  
713 Movement intention after parietal cortex stimulation in humans. *Science*, 324(5928), 811-  
714 813. doi: 10.1126/science.1169896
- 715 Dixon, P., McAnsh, S., & Read, L. (2012). Repetition effects in grasping. *Canadian Journal of*  
716 *Experimental Psychology*, 66(1), 1-17. doi: 0.1037/a0026192
- 717 Ellis, R. & Tucker, M. (2000). Micro-affordance: The potentiation of components of action by  
718 seen objects. *British Journal of Psychology*, 91, 451-471. Retrieved from  
719 <https://www.ncbi.nlm.nih.gov/pubmed/11104173>
- 720 Garcin, R., Rondot, P., & De Recondo, J. (1967). Optic ataxia localized in 2 left homonymous  
721 visual hemifields. *Revue Neurologique*, 116(6), 707-714.
- 722 Garrido-Vásquez, P. & Schubö, A. (2014). Modulation of visual attention by object affordance.  
723 *Frontiers in Psychology*, 5, 59. doi: 10.3389/fpsyg.2014.00059
- 724 Ghez, J., Gordon, J., & Ghilardi, M.F. (1995). Impairments of reaching movements in patients  
725 without proprioception. II. Effects of visual information on accuracy. *Journal of*  
726 *Neurophysiology*, 73(1), 361-372. Retrieved from  
727 <https://www.ncbi.nlm.nih.gov/pubmed/7714578>

- 728 Goldenberg, G. (1995). Imitating gestures and manipulating a manikin. The representation of  
729 the human body in ideomotor apraxia. *Neuropsychologia*, 33(1), 63-72. doi:  
730 10.1016/0028-3932(94)00104-W
- 731 Goldenberg, G. (2009). Apraxia and the parietal lobes. *Neuropsychologia*, 47(6), 1449-1459.  
732 doi: 10.1016/j.neuropsychologia.2008.07.014
- 733 Goldenberg, G., & Hagmann, S. (1998). Tool use and mechanical problem solving in apraxia.  
734 *Neuropsychologia*, 36, 581-589. Retrieved from  
735 <https://www.ncbi.nlm.nih.gov/pubmed/9723930>
- 736 Goldenberg, G., Münsinger, U., & Karnath, H.O. (2009). Severity of neglect predicts accuracy  
737 of imitation in patients with right hemisphere lesions. *Neuropsychologia*, 47(13), 2948-  
738 2952. doi: 10.1016/j.neuropsychologia.2009.06.024
- 739 Grafton, S.T., Fadiga, L., Arbib, M.A., & Rizzolatti, G. (1997). Premotor cortex activation  
740 during observation and naming of familiar tools. *Neuroimage*, 6(4), 231-236. doi:  
741 10.1006/nimg.1997.0293
- 742 Grea, H., Pisella, L., Rossetti, Y., Desmurget, M., Tilikete, C., Grafton, S., ... & Vighetto, A.  
743 (2002). A lesion of the posterior parietal cortex disrupts on-line adjustments during  
744 aiming movements. *Neuropsychologia*, 40, 2471-2480.
- 745 Hartmann, K., Goldenberg, G., Daumüller, M., & Hermsdörfer, J. (2005). It takes the whole  
746 brain to make a cup of coffee: The neuropsychology of naturalistic actions involving  
747 technical devices. *Neuropsychologia*, 43(4), 625-637. doi:  
748 10.1016/j.neuropsychologia.2004.07.015
- 749 Himmelbach, M., & Karnath, H.-O. (2005). Dorsal and ventral stream interaction:  
750 Contributions from optic ataxia. *Journal of Cognitive Neuroscience*, 17(4), 632-640. doi:  
751 10.1162/0898929053467514

- 752 Himmelbach, M., Nau, M., Zündorf, I., Erb, M., Perenin, M.-T., & Karnath, H.-O. (2009). Brain  
753 activation during immediate and delayed reaching in optic ataxia. *Neuropsychologia*, 47,  
754 1508-1517. doi: 10.1016/j.neuropsychologia.2009.01.033
- 755 Jacob, S.S., Jacob, S., Albornoz, A.M., & Biswas, D. (2002). Balint's syndrome: Missed or  
756 mistaken? *The American Journal of Medicine*, 112(6), 509-510.
- 757 Jarry, C., Osiurak, F., Delafuys, D., Chauviré, V., Etcharry-Bouyx, F., & Le Gall, D. (2013).  
758 Apraxia of tool use: More evidence for the technical reasoning hypothesis. *Cortex*, 49(9),  
759 2322-2333. doi: 10.1016/j.cortex.2013.02.011
- 760 Jax, S.A., & Buxbaum, L.J. (2013). Response interference between functional and structural  
761 object-related actions is increased in patients with ideomotor apraxia. *Journal of*  
762 *Neuropsychology*, 7(1), 12-18. doi: 10.1111/j.1748-6653.2012.02031.x
- 763 Jax, S.A., Buxbaum, L.J., & Moll, A.D. (2006). Deficits in movement planning and intrinsic  
764 coordinate control in ideomotor apraxia. *Journal of Cognitive Neuroscience*, 18(12),  
765 2063-2076. doi: 10.1162/jocn.2006.18.12.2063
- 766 Jeannerod, M (1986) Mechanisms of visuomotor coordination: A study of normal and brain-  
767 damaged subjects. *Neuropsychologia*, 24, 41-78.
- 768 Jeannerod, M., Decety, J., & Michel, F. (1994). Impairment of grasping movements following  
769 a bilateral posterior lesion. *Neuropsychologia*, 32(4), 369-380.
- 770 Karniel, A., & Inbar, G.F. (1997). A model for learning human reaching movements. *Biological*  
771 *Cybernetics*, 77(3), 173-183. doi: 10.1007/s004220050378
- 772 Kertesz, A. (1979). *Aphasia and related disorders*. New York: Grune & Stratton.

- 773 Lesourd, M., Baumard, J., Jarry, C., Etcharry-Bouyx, F., Belliard, S., Moreaud, O., ... &  
774 Osiurak, F. (2015). Mechanical problem-solving strategies in Alzheimer's disease and  
775 semantic dementia. *Neuropsychology*, 30(5), 612-623. doi: 10.1037/neu0000241
- 776 Lhermitte, J. (1939). *L'image de notre corps*. Paris: L'Harmattan.
- 777 Lindenberg, R., Renga, V., Zhu, L.L., Nair, D., Schlaug, G. (2010). Bihemispheric brain  
778 stimulation facilitates motor recovery in chronic stroke patients. *Neurology*, 27, 2176-  
779 2184. doi: 10.1212/WNL.0b013e318202013a
- 780 Luria, A.R. (1966). *Higher cortical functions in man*. New York, NY: Basic Books.
- 781 Marteniuk, R.G., MacKenzie, C.L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints  
782 on human arm movement trajectories. *Canadian Journal of Psychology*, 41(3), 365-378.
- 783 Mattingley, J.B., Husain, M., Rorden, C., Kennard, C., & Driver, J. (1998). Motor role of human  
784 inferior parietal lobe revealed in unilateral neglect patients. *Nature*, 392, 179-182.
- 785 Milner, A.D., Dijkerman, H.C., Pisella, L., McIntosh, R.D., Tilikete, C., Vighetto, A., &  
786 Rossetti, Y. (2001). Grasping the past: Delay can improve visuomotor performance.  
787 *Current Biology*, 11(23), 1896-1901. doi: 10.1016/S0960-9822(01)00591-7
- 788 Moscote-Salazar, L.R., Calderon-Miranda, W.G., Carmona-Meza, Z.A., Alvis-Miranda, H.R.,  
789 Churio, N.Z., Alcalá-Cerra, G., & Rubiano, A.M. (2016). Post-traumatic Balint's  
790 syndrome: A case report and review of the literature. *Bulletin of Emergency and Trauma*,  
791 4(2), 113-115.
- 792 Mummery, C.J., Patterson, K., Price, C.J., Ashburner, J., Frackowiak, R.S., & Hodges, J.R.  
793 (2000). A voxel-based morphometry study of semantic dementia: Relationship between  
794 temporal lobe atrophy and semantic memory. *Annals of Neurology*, 47(1), 36-45.  
795 Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/10632099>

- 796 Newman, S.D., Carpenter, P.A., Varma, S., & Just, M.A. (2003). Frontal and parietal  
797 participation in problem solving in the Tower of London: fMRI and computational  
798 modeling of planning and high-level perception. *Neuropsychologia*, 41(12), 1668-1682.  
799 Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/12887991>
- 800 Osiurak, F. (2014). What neuropsychology tells us about human tool use? The four constraints  
801 theory (4CT): mechanics, space, time, and effort. *Neuropsychology Review*, 24(2), 88-  
802 115. doi: 10.1007/s11065-014-9260-y
- 803 Osiurak, F., Aubin, G., Allain, P., Jarry, C., Etcharry-Bouyx, F., Richard, I., & Le Gall, D.  
804 (2008). Different constraints on grip selection in brain-damaged patients. Object use  
805 versus object transport. *Neuropsychologia*, 46(9), 2431-2434. doi:  
806 10.1016/j.neuropsychologia.2008.03.018
- 807 Osiurak, F. & Badets, A. (2016). Tool use and affordance: Manipulation-based versus  
808 reasoning-based approaches. *Psychological Review*, 123(5), 534-568. doi:  
809 10.1037/rev0000027
- 810 Osiurak, F., Jarry, C., & Le Gall, D. (2010). Grasping the affordances, understanding the  
811 reasoning: Toward a dialectical theory of human tool use. *Psychological Review*, 117(2),  
812 517-540. doi: 10.1037/a0019004
- 813 Osiurak, F., Jarry, C., & Le Gall, D. (2011). Re-examining the gesture engram hypothesis. New  
814 perspectives on apraxia of tool use. *Neuropsychologia*, 49,299-312. doi:  
815 10.1016/j.neuropsychologia.2010.12.041
- 816 Osiurak, F. & Le Gall, D. (2014). Apraxia: A gestural or a cognitive disorder? *Brain*, 138(3),  
817 e333. doi: 10.1093/brain/awu238

- 818 Perenin, M.T., & Vighetto, A. (1988). Optic ataxia: A specific disruption in visuomotor  
819 mechanisms. I. Different aspects of the deficit for reaching for objects. *Brain*, 111(3), 643-  
820 674. Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/3382915>
- 821 Perez, F.M., Tunkel, R.S., Lachmann, E.A., & Nagler, W. (1996). Balint's syndrome arising  
822 from bilateral posterior cortical atrophy or infarction: Rehabilitation strategies and their  
823 limitation. *Disability and Rehabilitation*, 18(6), 300-304.
- 824 Pisella, L., Grea, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G., ... & Rossetti, Y.  
825 (2000). An 'automatic pilot' for the hand in human posterior parietal cortex: Toward  
826 reinterpreting optic ataxia. *Nature Neuroscience*, 3(7), 729-736. doi: 10.1038/76694
- 827 Prigatano, P. G. (1999). *Principles of neuropsychological rehabilitation*. New York: Oxford  
828 University Press.
- 829 Randerath, J., Li, Y., Goldenberg, G., & Hermsdörfer, J. (2009). Grasping tools: Effects of task  
830 and apraxia. *Neuropsychologia*, 47(2), 497-505. doi:  
831 10.1016/j.neuropsychologia.2008.10.005
- 832 Randerath, J., Valyear, K.F., Hood, A., & Frey, S.H. (2015). Two routes to the same action: An  
833 action repetition priming study. *Journal of Motor Behavior*, 47(2), 142-152. doi:  
834 10.1080/00222895.2014.961891
- 835 Revol, P., Rossetti, Y., Vighetto, A., Rode, G., Boisson, D., & Pisella, L. (2003). Pointing errors  
836 in immediate and delayed conditions in unilateral optic ataxia. *Spatial Vision*, 16(3-4),  
837 347-364. Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/12858956>
- 838 Reynaud, E., Lesourd, M., Navarro, J., & Osiurak, F. (2016). On the neurocognitive origins of  
839 human tool use: A critical review of neuroimaging data. *Neuroscience and biobehavioral*  
840 *Reviews*, 64, 421-437. doi: 10.1016/j.neubiorev.2016.03.009

- 841 Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying  
842 the understanding and imitation of action. *Nature Reviews. Neuroscience*, 2(9), 661-670.  
843 doi: 10.1038/35090060
- 844 Rosenbaum, D.A., Chapman, K.M., Weigelt, M., Weiss, D.J., & Van der Wel, R. (2012).  
845 Cognition, action, and object manipulation. *Psychological Bulletin*, 138(5), 924-946. doi:  
846 10.1037/a0027839
- 847 Rosselli, M., Ardila, A., & Beltran, C. (2001). Rehabilitation of Balint's syndrome: A single  
848 case report. *Applied Neuropsychology*, 8(4), 242-247. doi:  
849 10.1207/S15324826AN0804\_7
- 850 Rossetti, Y., & Pisella, L. (2018). Optic ataxia: Beyond the dorsal stream cliché. *Handbook of*  
851 *Clinical Neurology*, 151, 225-247. doi: 10.1016/B978-0-444-63622-5.00011-5
- 852 Rossetti, Y., Pisella, L., & Vighetto, A. (2003). Optic ataxia revisited: Visually guided action  
853 versus immediate visuomotor control. *Experimental Brain Research*, 153(2), 171-179.  
854 doi: 10.1007/s00221-003-1590-6
- 855 Rossetti, Y., Pisella, L., & McIntosh, R.D. (2017). Rise and fall of the two visual systems  
856 theory. *Annals of Physical and Rehabilitation Medicine*, 60(3), 130-140. doi:  
857 10.1016/j.rehab.2017.02.002
- 858 Rossetti, Y., Revol, P., McIntosh, R., Pisella, L., Rode, G., Danckert, J., ... & Milner, A.D.  
859 (2005). Visually guided reaching: Bilateral posterior parietal lesions cause a switch from  
860 fast visuomotor to slow cognitive control. *Neuropsychologia*, 43, 162-177. doi:  
861 10.1016/j.neuropsychologia.2004.11.004
- 862 Rossetti, Y., Rode, G., & Goldenberg, G. (2005). Perspectives in higher-order motor deficit  
863 rehabilitation: Which approach for which ecological result? In H.-F. Freund, M.  
864 Jeannerod, M. Hallett & R. Leiguarda (Eds.). *Higher-order motor disorders, from*

- 865 neuroanatomy and neurobiology to clinical neurology (pp. 475-498). Oxford: Oxford  
866 University Press.
- 867 Rothi, L.J.G., Ochipa, C., & Heilman, K.M. (1991). A cognitive neuropsychological model of  
868 limb praxis. *Cognitive Neuropsychology*, 8, 443-458. doi: 10.1080/02643299108253382
- 869 Roy, E.A., & Square, P.A. (1985). Common considerations in the study of limb, verbal and oral  
870 apraxia. In E. A. Roy (Ed.), *Neuropsychological studies of apraxia and related disorders*  
871 (pp. 111–161). Amsterdam: Elsevier.
- 872 Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal*  
873 *Society of London B*, 298, 199-209. Retrieved from  
874 <https://www.ncbi.nlm.nih.gov/pubmed/6125971>
- 875 Sirigu, A., Cohen, L., Duhamel, J.R., Pillon, B., Dubois, B., & Agid, Y. (1995). A selective  
876 impairment of hand posture for object utilization in apraxia. *Cortex*, 31(1), 41-55.  
877 Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/7781320/>
- 878 Smania, N., Girardi, F., Domenicali, C., Lora, E., & Aglioti, S. (2000). The rehabilitation of  
879 limb apraxia: A study in left-brain-damaged patients. *Archives of Physical Medicine and*  
880 *Rehabilitation*, 81(4), 379-388. doi: 10.1053/mr.2000.6921
- 881 Thielman, G., Kaminski, T., & Gentile, A.M. (2008). Rehabilitation of reaching after stroke:  
882 Comparing 2 training protocols utilizing trunk restraint. *Neurorehabilitation and Neural*  
883 *Repair*, 22(6), 697-705. doi: 10.1177/1545968308315998
- 884 Valyear, K.F., Culham, J.C., Sharif, N., Westwood, D., & Goodale, M.A. (2006). A double  
885 dissociation between sensitivity to changes in object identity and object orientation in the  
886 ventral and dorsal visual streams: A human fMRI study. *Neuropsychologia*, 44(2), 218-  
887 228. doi: 10.1016/j.neuropsychologia.2005.05.004

- 888 Valyear, K.F. & Frey, S.H. (2014). Hand selection for object grasping is influenced by recent  
889 motor history. *Psychonomic Bulletin & Review*, 21(2), 566-573. doi: 10.3758/s13423-  
890 013-0504-2
- 891 Vingerhoets, G. (2014). Contribution of the posterior parietal cortex in reaching, grasping, and  
892 using objects and tools. *Frontiers in Psychology*, 5. doi: 10.3389/fpsyg.2014.00151
- 893 Zgaljardic, D.J., Yancy, S., Levinson, J., Morales, G., Masel, B.E. (2011). Balint's syndrome  
894 and post-acute brain injury rehabilitation: A case report. *Brain Injury*, 25(9), 909-917. doi:  
895 10.3109/02699052.2011.585506
- 896

897

## **FOOTNOTES**

898

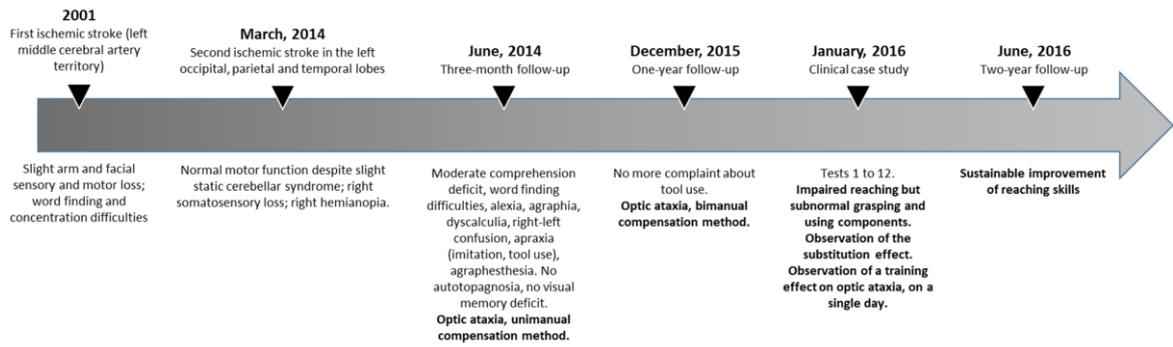
There is no footnote in the manuscript.

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902 Figure 1



903

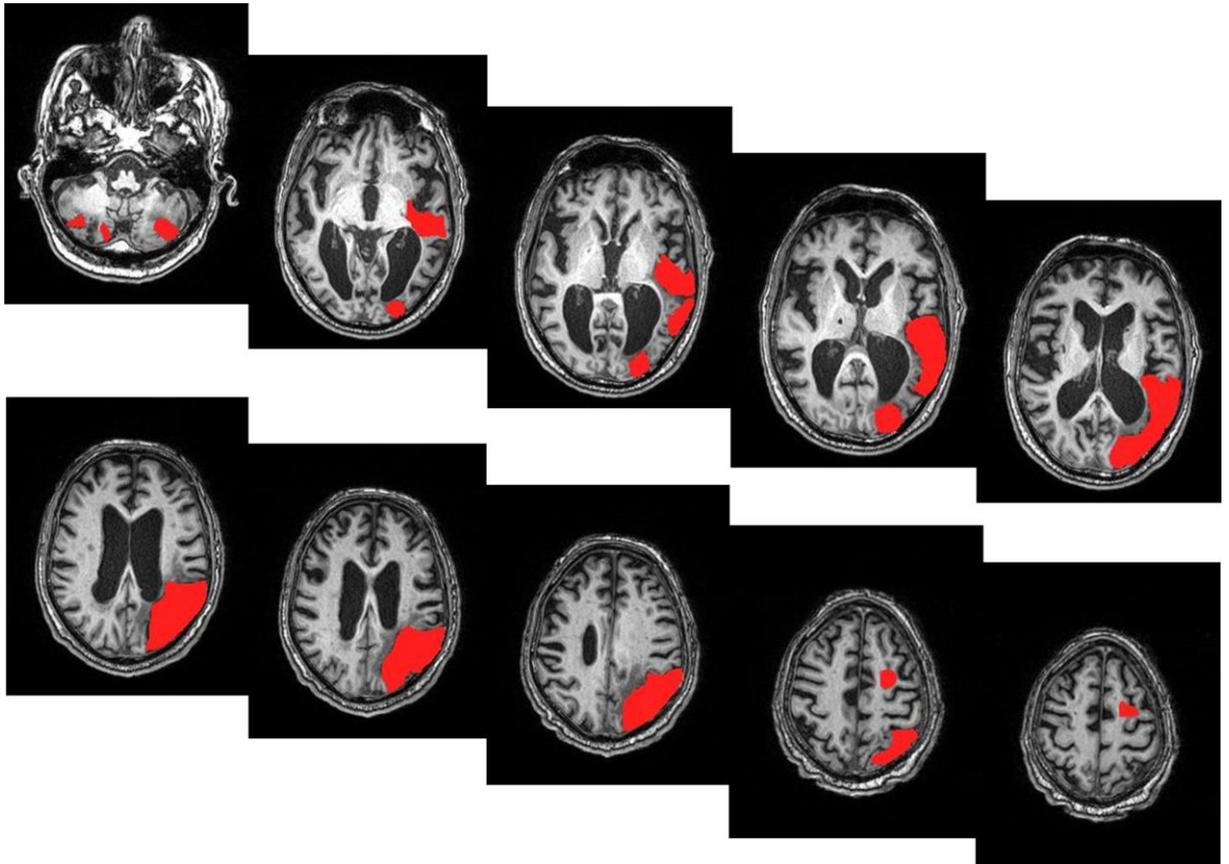
904 Timeline of clinical assessment. Note. The text in bold corresponds to the main observations

905 and conclusions of the study

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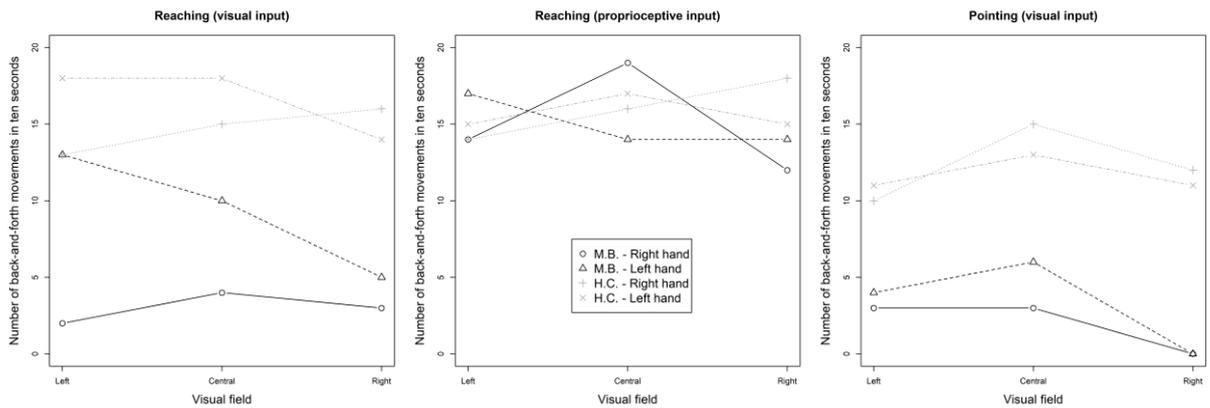
Figure 2



908

909 Lesions of patient M.B. Note. The left hemisphere is on the right side. M.B.'s lesions were  
910 manually colored in red on the most significant standard templates of the atlas, then lesion sites  
911 were carried over to M.B.'s MRI images.  
912

913 Figure 3



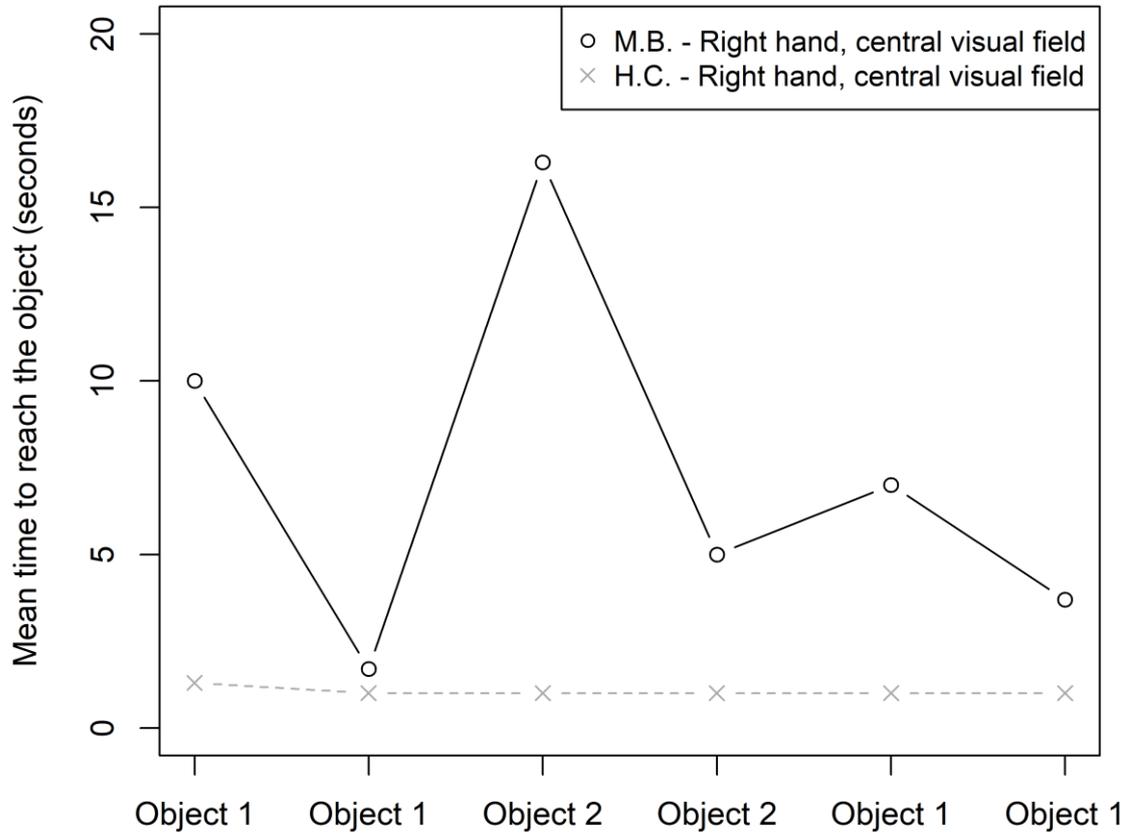
914

915 Hand, field and task effects on M.B.'s reaching performance. Note. Values correspond to the  
 916 total number of back-and-forth movements, summed up across items. H.C.: Performance of one  
 917 70-year-old man. M.B. demonstrated a bimanual reaching deficit more marked in the right hand  
 918 (Test 1). The reaching performance improved under proprioceptive input (Test 2). The pointing  
 919 condition confirmed the presence of right hemianopia (Test 3) but the latter does not explain  
 920 slowness in the left and central visual fields. M.B.'s performance was poorer than H.C.'s in Test 3  
 921 because he was not familiar with the use of a laser.

922

923

Figure 4

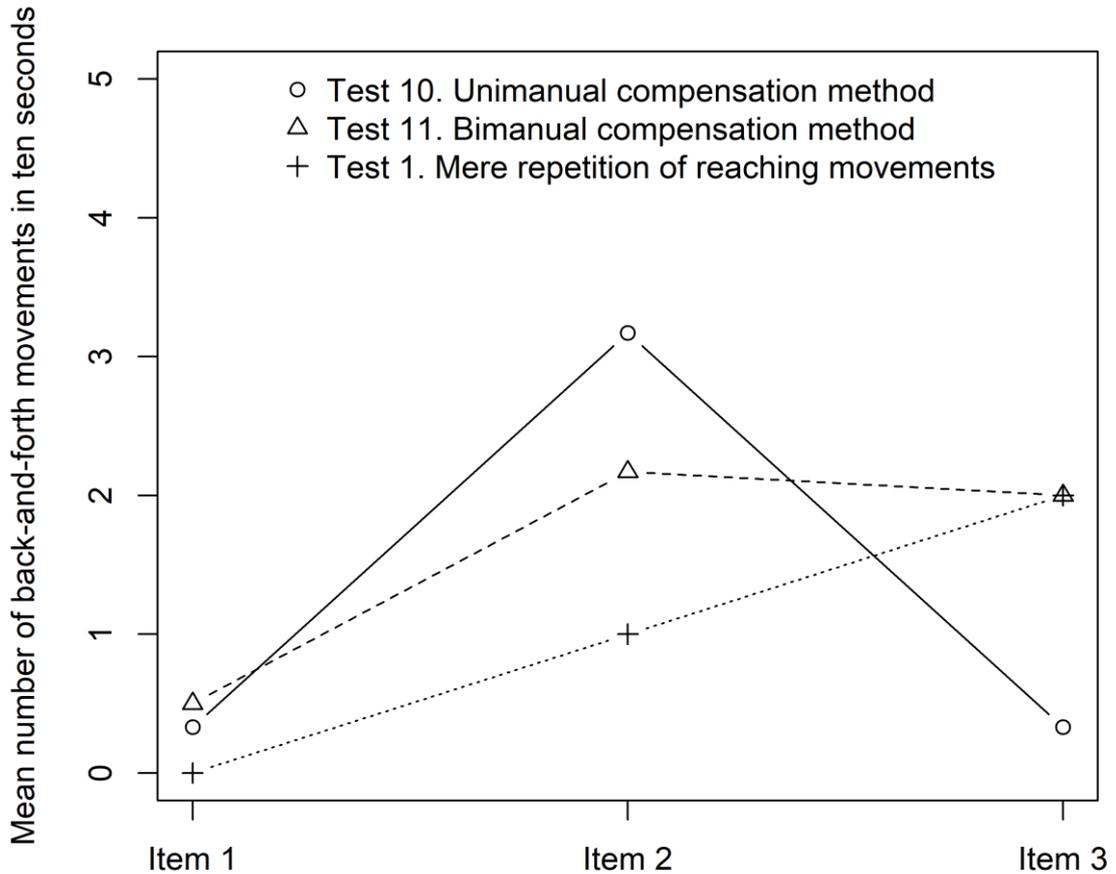


924

925 Effect of object substitution on M.B.'s reaching performance. Note. "Object 1" and "Object 2"  
926 refer to object changes. As shown in Table 1, there were 3 blocks (one for each object size) of 6  
927 items each presented in the following order: Object 1, Object 1, Object 2, Object 2, Object 1, Object  
928 1. For example: Coin, Coin, Paper clip, Paper clip, Coin, Coin. Values correspond to the mean  
929 reaching time across the three blocks.

930

931 Figure 5



932

933 Comparison of two compensation methods. Note. Values correspond to the mean number  
 934 of backand-forth movements toward a wooden cube. Test 10 (Unimanual compensation method):  
 935 M.B. reached the object with his right hand (Item 1), then the next one with his left hand (Item 2)  
 936 and the next one with his right hand again (Item 3). Test 11 (Bimanual compensation method):  
 937 M.B. reached the object with his right hand (Item 1), then the next one with his right hand guided  
 938 by his left hand (Item 2) and the next one with his right hand again (Item 3). Test 1: M.B. reached  
 939 the object with his right hand in all of the three items. In details, scores of M.B. in items 1 and 3 of  
 940 each series were compared for each visual field. With the unimanual method, no improvement  
 941 was observed (+0, +0.5 and -0.5 mean back-and-forth movements in the left, central and right

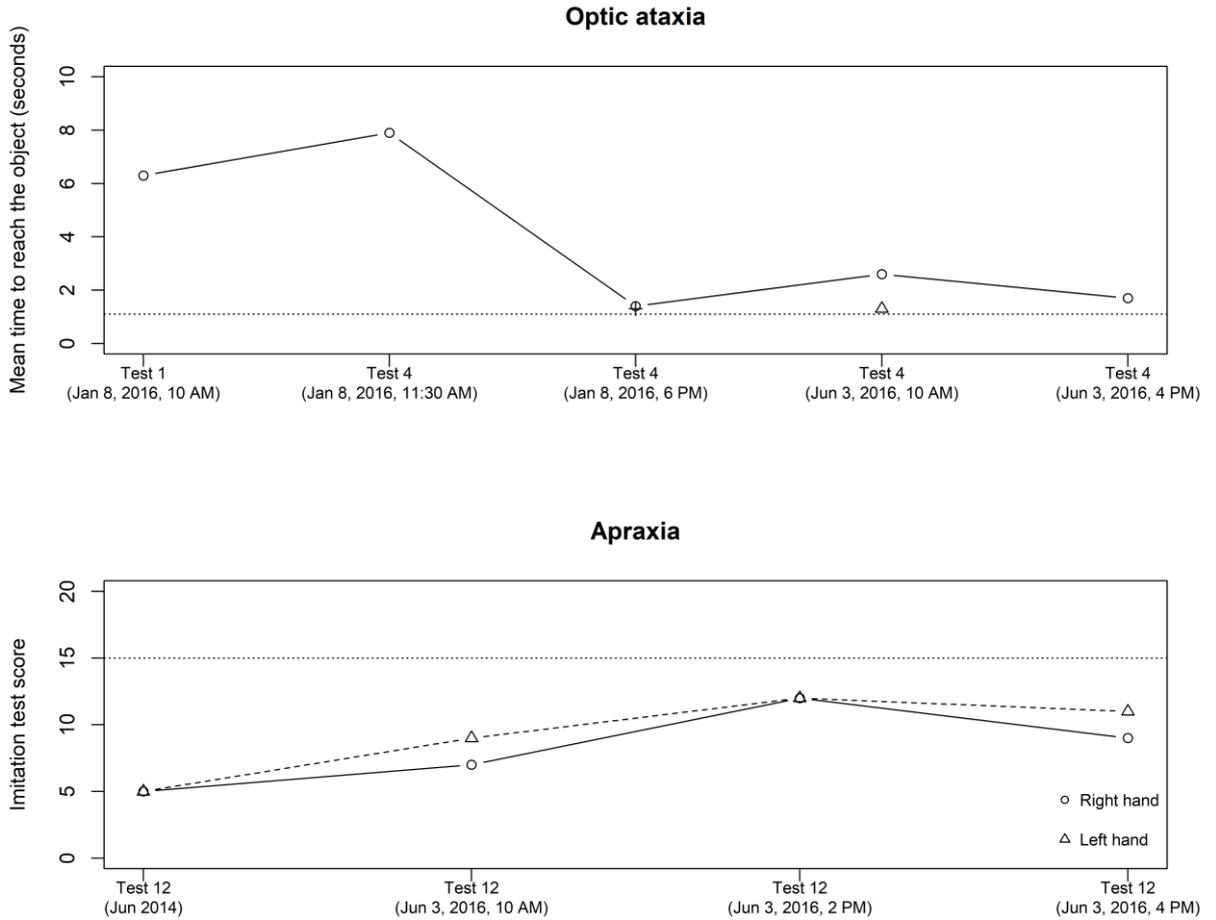
*Repetitive reaching in optic ataxia*

942 visual fields, respectively). In contrast, the bimanual method appeared quite effective (+1, +3.5  
943 and +0). In all likelihood, hemianopia accounts for the lack of improvement in the right visual field.  
944 Mere repetition (Test 1) was effective too (+2, +3 and +1).

945

946

Figure 6



947

948 Effect of repetition on optic ataxia, in comparison with apraxia. Note. Upper panel: Optic  
 949 ataxia. All results concern only the right hand. “+”: mean reaching time with four alternative  
 950 objects (right hand). “Δ”: mean reaching time in Test 4, using the left hand. The horizontal dotted  
 951 line corresponds to the mean reaching time of one healthy 70-year-old man in Test 4. Lower panel:  
 952 Apraxia. The horizontal dotted line corresponds to the minimum score observed in a sample of  
 953 104 healthy controls recruited for another study (age range: 50-89 years old).

954

955

**TABLE 1. LIST OF ITEMS FOR THE ASSESSMENT OF OPTIC**

956 **ATAXIA**

Item number	Tests 1, 2 and 3		Tests 4, 5 and 9 (right hand, central VF)				Test10	Test 11	Tests 10 & 11
	Hand	Visual field	Object	Expected grip	Size	Changes in shape	Hand	Hand	Visual field
01	Right	Right	Coin	Precision	Small	Object 1	Right	Right	Right
02	Right	Right	Coin	Precision	Small	Object 1	Left	Right + Left	Right
03	Right	Right	Paper clip	Precision	Small	Object 2	Right	Right	Right
04	Right	Left	Paper clip	Precision	Small	Object 2	Right	Right	Left
05	Right	Left	Coin	Precision	Small	Object 1	Left	Right + Left	Left
06	Right	Left	Coin	Precision	Small	Object 1	Right	Right	Left
07	Right	Central	Lighter	Precision	Medium	Object 1	Right	Right	Central
08	Right	Central	Lighter	Precision	Medium	Object 1	Left	Right + Left	Central
09	Right	Central	Inhaler	Precision	Medium	Object 2	Right	Right	Central
10	Left	Left	Inhaler	Precision	Medium	Object 2	Right	Right	Left
11	Left	Left	Lighter	Precision	Medium	Object 1	Left	Right + Left	Left
12	Left	Left	Lighter	Precision	Medium	Object 1	Right	Right	Left
13	Left	Right	Large cube	Power	Large	Object 1	Right	Right	Right
14	Left	Right	Large cube	Power	Large	Object 1	Left	Right + Left	Right
15	Left	Right	Pen holder	Power	Large	Object 2	Right	Right	Right
16	Left	Central	Pen holder	Power	Large	Object 2	Right	Right	Central
17	Left	Central	Large cube	Power	Large	Object 1	Left	Right + Left	Central
18	Left	Central	Large cube	Power	Large	Object 1	Right	Right	Central

957 *Note.* Only the tests assessing either reaching or grasping are displayed here. Tests 1, 2 and 3 served

958 to diagnose optic ataxia. Tests 4 and 5 demonstrated the dissociation between reaching and grasping. Tests

959 6, 7 and 8 assessed the using component of action (i.e., planning skills, semantic memory, technical

960 reasoning). Test 9 corresponded to the same testing session as Tests 4 and 5, and was used to demonstrate

961 the substitution effect. Tests 10 and 11 studied M.B.'s compensation strategies (i.e., the unimanual and the

962 bimanual methods, respectively). Test 12 assessed visuo-imitative apraxia. VF: Visual field.

963

964

965

966 **TABLE 2. RESULTS OF M.B. DEPENDING ON COMPONENTS OF**

967 **ACTION**

	M.B.'s performance		Control sample
	Mean time in seconds (SD)	Score	Mean (range)
<b>Test 4.</b> Reach to grasp (reaching, right hand)	7.3 (7.5)	-	1.1 (1-2) <sup>a</sup>
<b>Test 5.</b> Reach to grasp (grasping, right hand)	-	15/18	18/18 <sup>a</sup>
<b>Test 6.</b> Tower of London	-	13/18	14.6/18 (9-18) <sup>b</sup>
<b>Test 7.</b> Picture matching	-	17/20	18.9/20 (14-20) <sup>b</sup>
<b>Test 8.</b> Mechanical problem solving	-	8/9	8.3/9 (5-9) <sup>b</sup>

968 *Notes.* <sup>a</sup> M.B.'s performance was compared to that of one healthy 70-year old man. Reaching was very slow

969 whereas grasping was subnormal; <sup>b</sup> M.B.'s performance was compared to that of 104 healthy controls

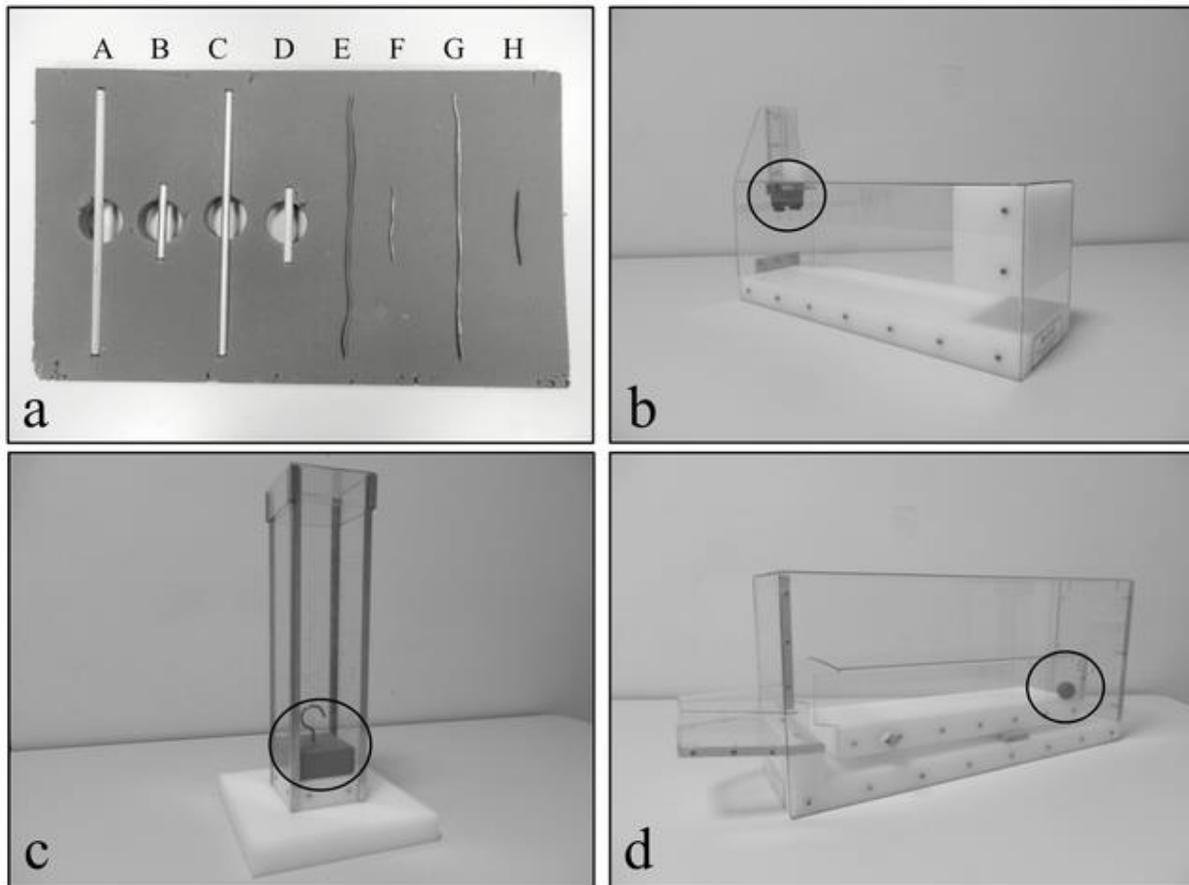
970 recruited for another study (age range: 50-89 years old). Single-case analysis (Crawford & Garthwaite,

971 2002) confirmed that M.B. scored in normal range in Test 6, Test 7 and Test 8 (all *ps* > .11).

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974 **SUPPLEMENTARY FIGURE 1. MATERIALS FOR THE MECHANICAL PROBLEM SOLVING TASK**



The rods (a) were as follows: [A. wood, L25 cm, Ø7 mm], [B. aluminium, L7 cm, Ø7 mm], [C. aluminium, L25 cm, Ø7 mm], [D. wood, L7 cm, Ø7 mm], [E. copper electrical wire, L25cm, Ø2mm], [F. tin wire, L7 cm, Ø2mm], [G. tin wire, L25 cm, Ø2 mm], [H. copper electrical wire, L7 cm, Ø2mm]. Preliminary testing indicated that Box 1 (b) was easier than Box 2 (c) and that the latter was easier than Box 3 (d).

For each box, the position of the target was clearly shown to participants and they were invited to examine carefully each side of the box. They were allowed to move and turn the boxes but not to tilt or lift them. As for other tests, they could use one or both hands. The test included one practice item: the participant was presented with a batten (23x3x3 cm) and a specific box (not to be used in experimental items) consisting of a transparent tunnel open at both ends (20x7x7 cm) and containing a red wooden bead. The participant was asked to extract the bead using the batten, which was possible by simply inserting the latter in the box and pushing the bead. In this item only, the examiner was allowed to demonstrate the solution for the participant to identify targets and to understand the purpose of the test.

Each box could be solved in two steps (a step was defined as a significant modification of the whole technical device that pointed towards the solution). For experimental box 1 (b), the solution was to insert a long rod into the “chimney” and to push the cube to bring it down (first stage). The second stage required pulling the cube out of the box. For box 2 (c), participants had to remove the lid by hand, then to create a hook with a flexible rod and

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to lift the target so as to disunite it from the bottom of the box (first stage). The second step was reached when the target was completely extracted from the box, which required the hook to be well shaped to avoid dropping the target. For box 3 (d), it was necessary to insert a rigid rod into the round hole and to use it as a lever to lift the mobile compartment contained inside the box. Then the bead rolled onto the entrance of the box (first step) and participants could retrieve it with a rod (second step).

For each box, two rods were critical to solve the problem (i.e., Box 1: **A, C**; Box 2: **E, G**; Box 3: **A, C**) but some other rods could be relevant depending on the status of the problem (i.e., Box 1: **A, C, E, G**; Box 2: only rods **E** and **H** were relevant; Box 3: **A, C, E, G**). None of the small rods were useful *per se*, however every rod could be actually relevant if combined with another rod.

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