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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.

39

KEYWORDS

40

Optic ataxia; reaching; grasping; rehabilitation; apraxia.

41

PRINTING

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We recommend printing in black-and-white.

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1. AIMS OF THE PRESENT STUDY

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

56

2. THEORETICAL BACKGROUND

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

60

2.1. REACHING, GRASPING AND USING COMPONENTS OF ACTION

61

2.1.1. Reaching

62 Reaching movements correspond to the hand trajectory toward the tool to be grasped,
63 independently of how the tool is subsequently grasped. They are proximal-to-distal, fast
64 movements with a straight line and a bell shape speed profile (Karniel & Inbar, 1997). In normal
65 human activity, reaching movements rely mainly on visuo-motor connections (Jeannerod, 1986).
66 They are thought to depend on characteristics of the body (e.g., proprioceptive input; Ghez,
67 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-Vásquez &
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.

197 -----

198 Please insert Figure 1 and Figure 2 about here.

199 -----

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.

248 -----

249 Please insert Table 1 and Figure 3 about here.

250 -----

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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897

FOOTNOTES

898

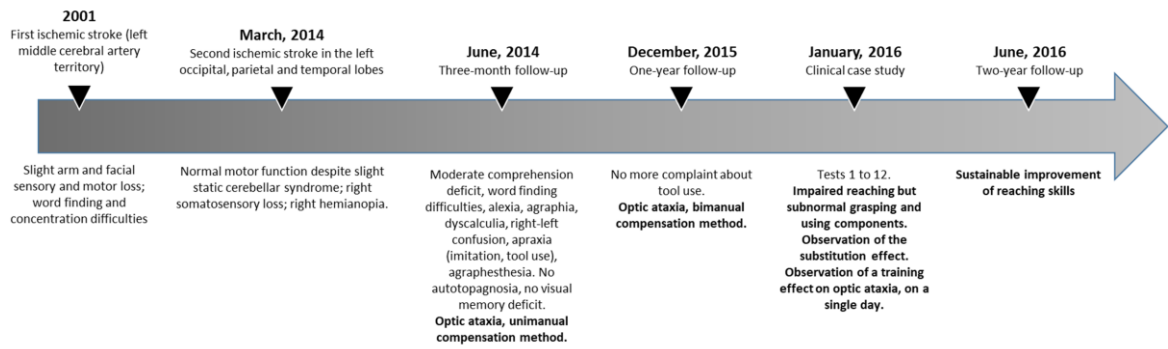
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902 Figure 1



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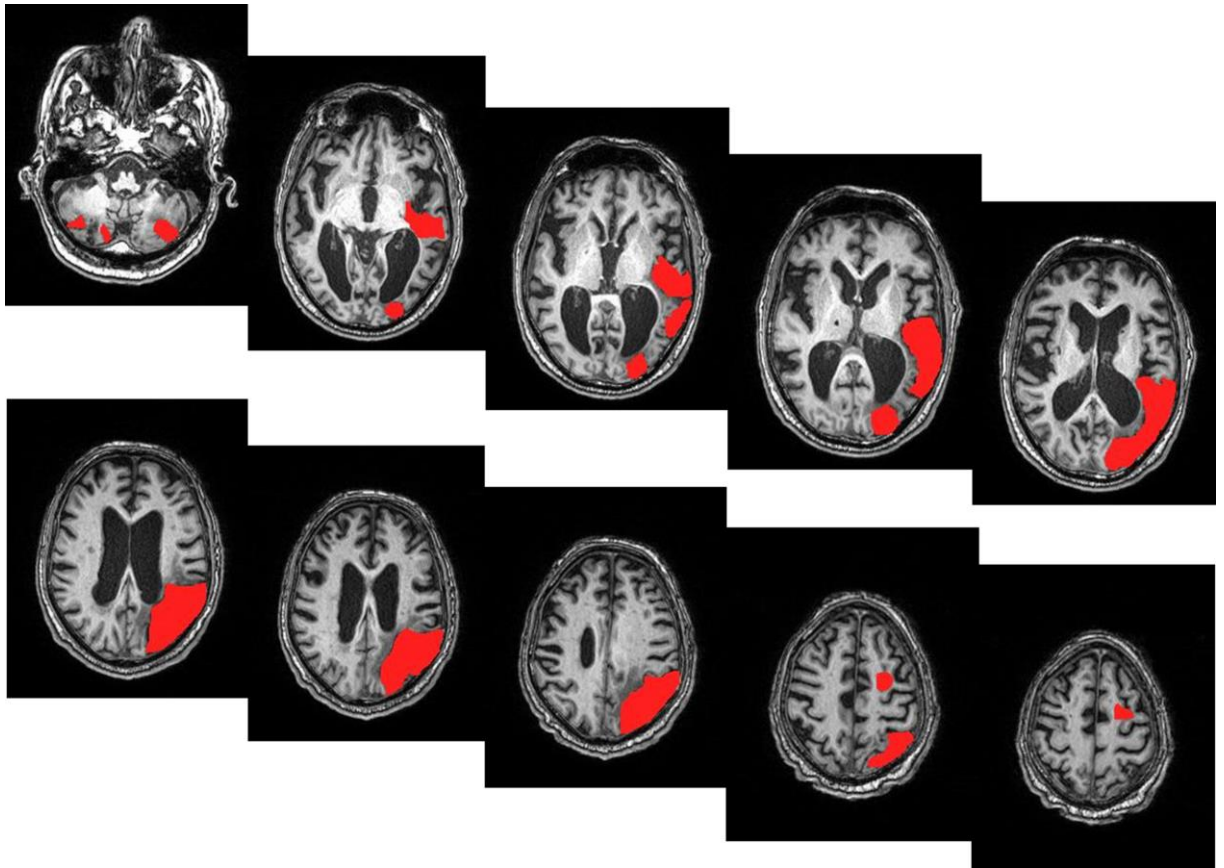
904 Timeline of clinical assessment. Note. The text in bold corresponds to the main observations

905 and conclusions of the study

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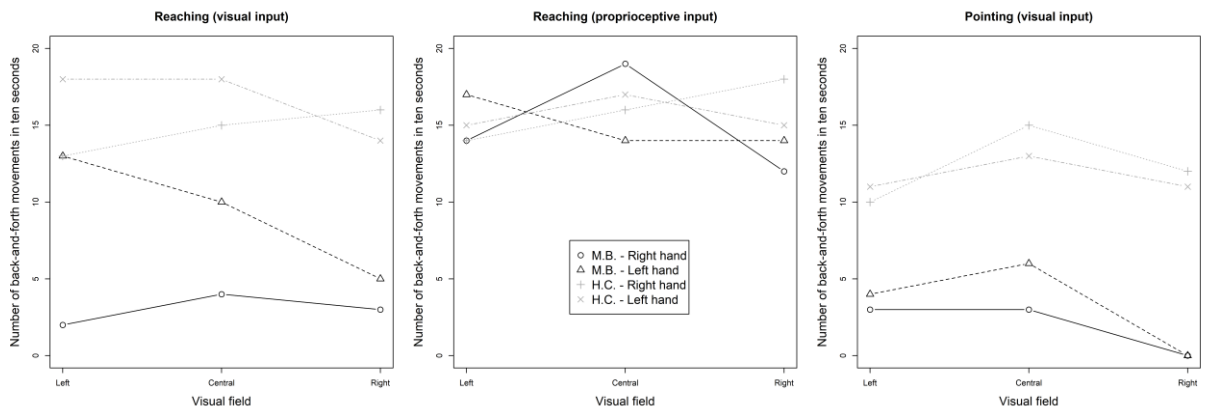
Figure 2



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



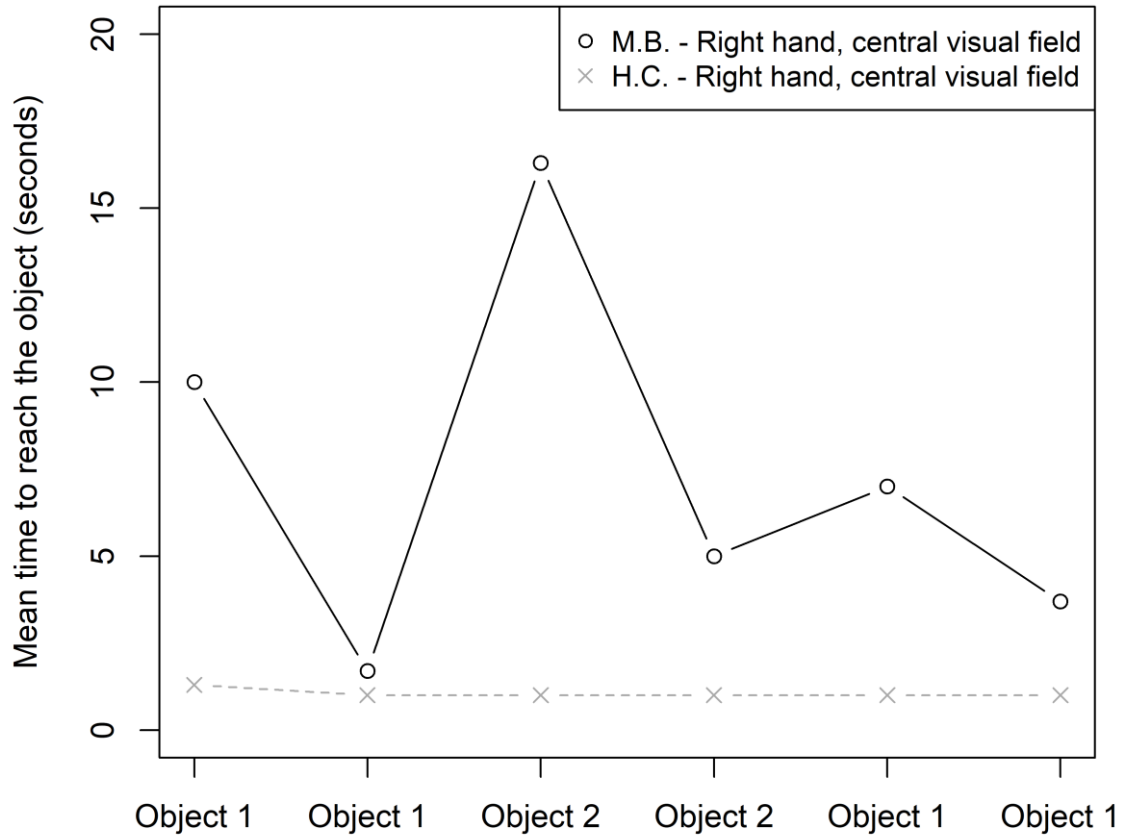
914

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

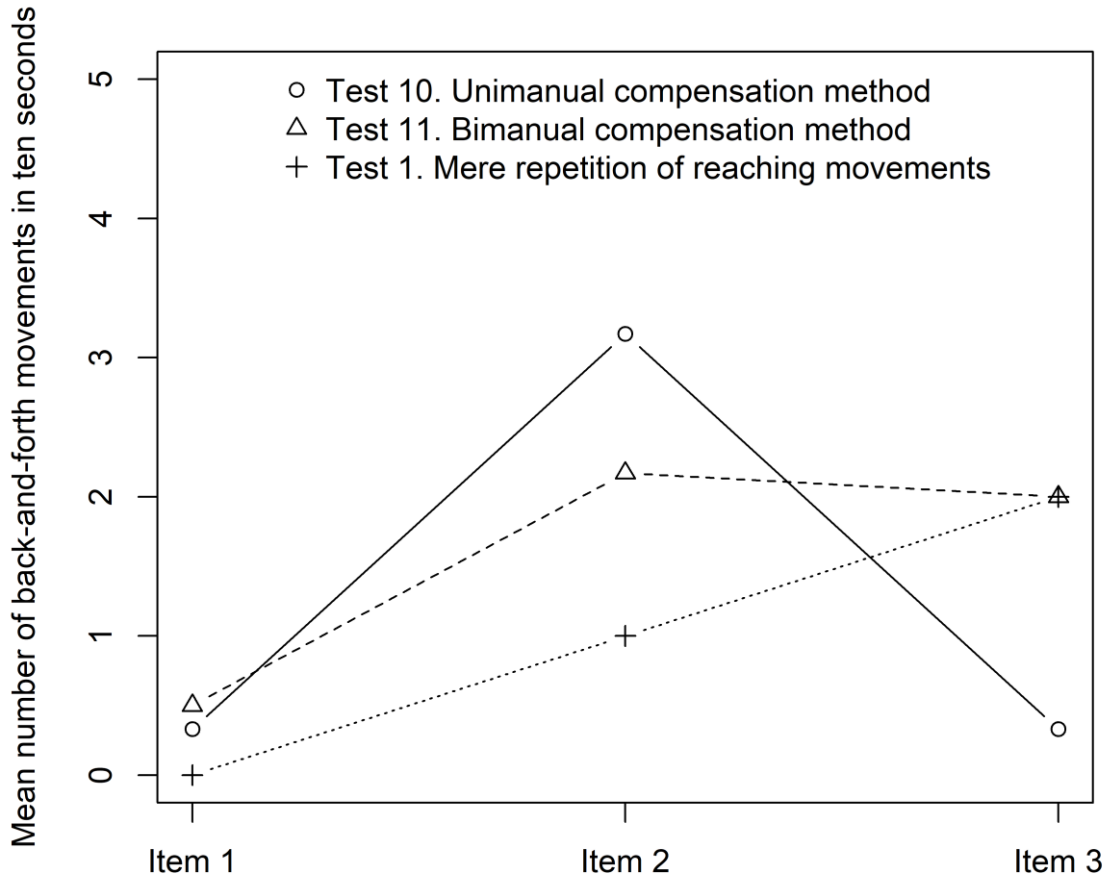


924

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

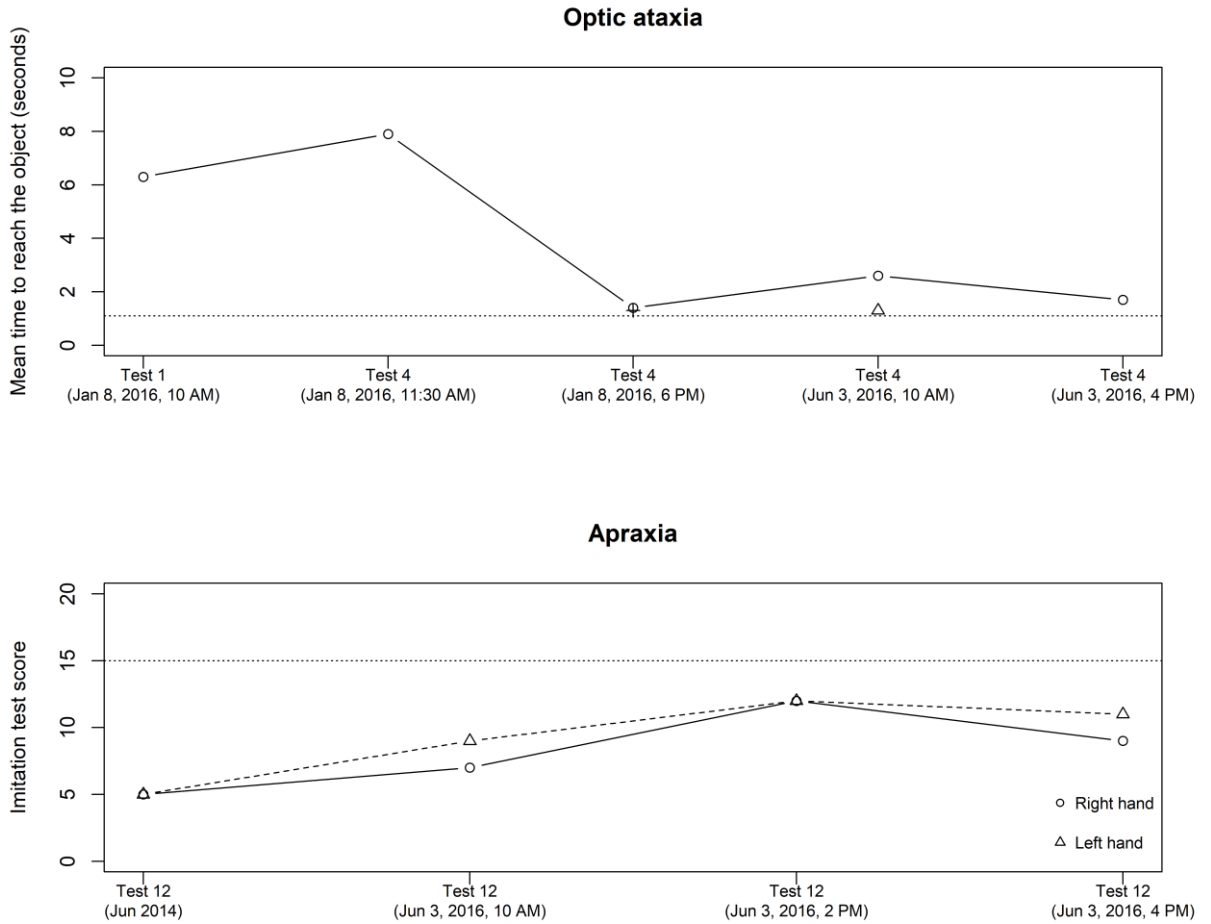
Repetitive reaching in optic ataxia

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)
Test 4. Reach to grasp (reaching, right hand)	7.3 (7.5)	-	1.1 (1-2) ^a
Test 5. Reach to grasp (grasping, right hand)	-	15/18	18/18 ^a
Test 6. Tower of London	-	13/18	14.6/18 (9-18) ^b
Test 7. Picture matching	-	17/20	18.9/20 (14-20) ^b
Test 8. Mechanical problem solving	-	8/9	8.3/9 (5-9) ^b

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

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

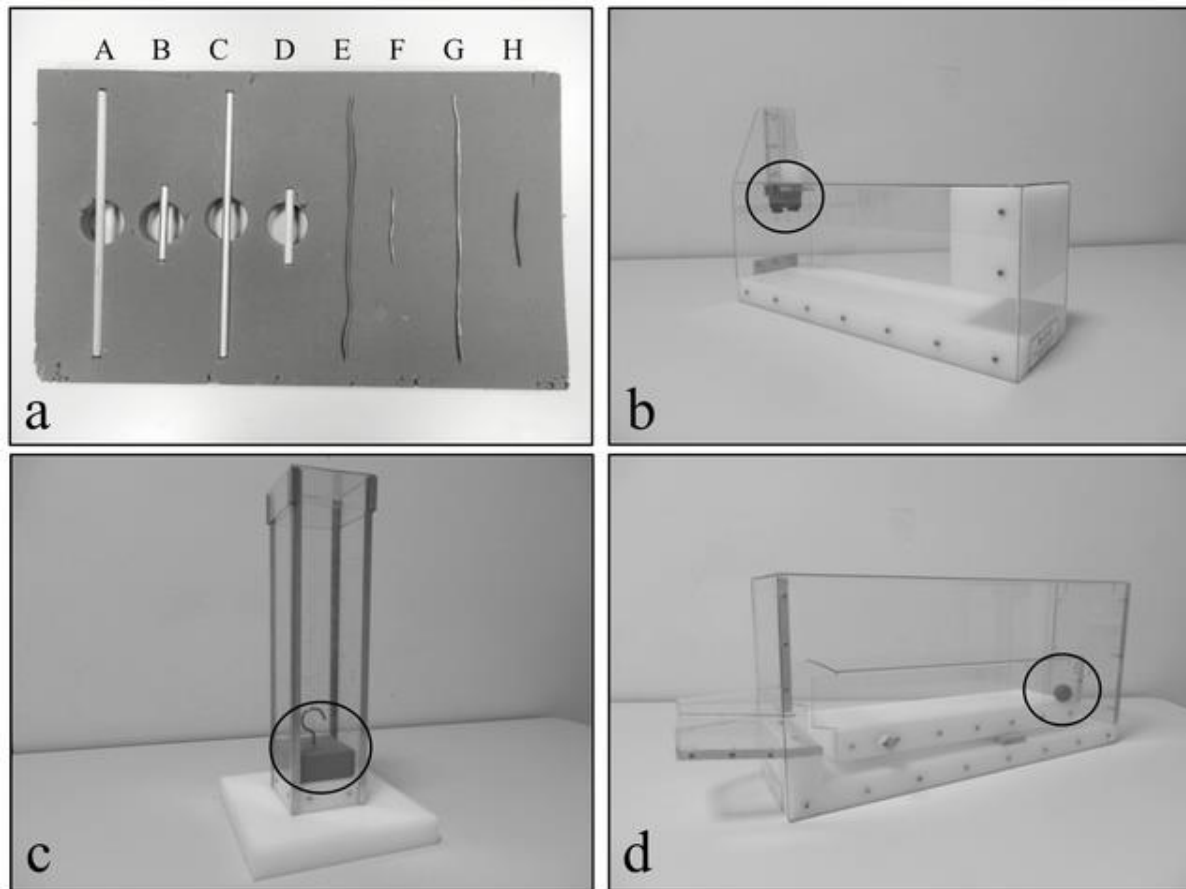
970 recruited for another study (age range: 50-89 years old). Single-case analysis (Crawford & Garthwaite,

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

972

973

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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