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## **Haptic shape perception deficit in spatial neglect is improved by Prism Adaptation**

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## Abstract

Neglect manifestations are typically explored in the visual modality. Although they are less commonly investigated tactile deficits also exist, and the aim of this study was to explore neglect in this modality. A haptic object discrimination task was designed to assess whether or not shape perception is impaired in right brain damaged patients with or without neglect. Each patient's performance on the object discrimination task was assessed before and after a brief period of prism adaptation, a bottom-up rehabilitation technique known to improve neglect symptoms. The results suggest that a haptic deficit – in the form of substantially more left errors – is present only in patients with neglect. Following prism adaptation, the left bias error rates in neglect patients were substantially reduced, and were similar to those observed in patients without neglect. Moreover, the haptic processing of the right side of objects also improved slightly. This finding suggests an expansion of the effects of prism adaptation to the unexposed, tactile modality supporting the cross-modal central effect hypothesis.

## **Prisms adaptation improves haptic object discrimination in hemispatial neglect.**

### Introduction

Spatial neglect, described more than a century ago (Anton, 1899; Balint, 1909; Zingerle, 1913; and Babinski, 1914) is characterized by a failure to respond to or orient towards novel or meaningful stimuli positioned on the side opposite the lesion (Heilman, 1985; Halligan *et al.*, 2003; Cubelli, 2017), without any primary sensory or motor deficits (Heilman, 1979; Kerkoff, 2001). A typical space-oriented behavioural disorder biased towards the right occurred, due to the predominance of right hemisphere lesions (Heilman, 1993; Vallar & Calzolari, 2018). Spontaneous recovery is frequent in the first 2-3 weeks following stroke (Hier *et al.*, 1983; Stone *et al.*, 1992; Cassidy *et al.*, 1998). Nevertheless, about 30% of patients still exhibit deficits three months post stroke, resulting in a chronic disorder (Levine *et al.*, 1986; Cassidy *et al.*, 1998; Cherney & Halper, 2001). The challenge to find rehabilitation methods that can alleviate neglect symptoms is all the more difficult given the wide range of clinical features observed in patients (see for review, Bisiach & Vallar, 1988). Neglect is most often depicted as a visual disorder affecting, for example mental imagery tasks (Bisiach & Luzatti, 1978; Rode *et al.*, 2001, 2007), and inducing debilitating effects on everyday life activities (Frassinetti *et al.*, 2002; Mizuno *et al.*, 2011) like wheelchair driving (*e.g.* Jacquin-Courtois *et al.*, 2008), and walking (Turton *et al.*, 2009). In the sensory domain, auditory (*e.g.* Bisiach *et al.*, 1984; Pavani *et al.*, 2004; Jacquin-Courtois *et al.*, 2010; Gutschalk & Dykstra, 2015), olfactory (Bellas *et al.*, 1988) and somatosensory (Maravita *et al.*, 2003; Dijkerman *et al.*, 2004) deficits remain much less studied and may appear less disabling than visual deficits (Gainotti, 2010). In the tactile modality, in the absence of vision, patients show a lack of awareness of tactile inputs delivered to the side of the body opposite the brain lesion, *i.e.* tactile neglect. These manifestations occur when stimulating skin mechanoreceptors, *i.e.* when stimuli are applied to the body surface, such as during tactile perception or pressure sensitivity tasks (Maravita *et al.*, 2003; Dijkerman *et al.*, 2004; Serino *et al.*, 2007), and during upper limb proprioceptive tasks, resulting in a position sense deficit (*e.g.* Vallar *et al.*, 1993). Deficits have also been reported when patients are engaged in a manual search task in extrapersonal space (De Renzi *et al.*, 1970; Chédru, 1976; Beshin *et al.*, 1996; Revol, 2000). In their seminal paper, De Renzi *et al.* (1970) asked right brain damaged patients to find a marble placed in the lateral arm of a maze hidden behind a

35 curtain. They found that neglect patients were slower and often missed the marble when it was  
36 placed in left space, suggesting a supramodal disorder of space representation (De Renzi *et al.*,  
37 1970). This error cannot be accounted for by a tactile or kinaesthetic perception impairment  
38 because the left part was properly explored in blindfolded neglect patients (Villardita *et al.*,  
39 1987). Even healthy controls may exhibit left errors in this task (Beshin *et al.*, 1996). So called  
40 “tactile line bisection” tasks have also been used with neglect patients, but have failed to detect  
41 any evidence of neglect phenomena (Fujii *et al.*, 1991; Hjaltason *et al.*, 1993), probably because  
42 of the use by patients of a counting strategy (*e.g.* Hatta & Yamamoto, 1986; McIntosh *et al.*,  
43 1999).

44 Haptic perception relies on the stimulation of mechanoreceptors through object  
45 manipulation, in order to identify an object or one of its components (*e.g.* size, shape, *e.g.*  
46 Gibson, 1962). Some haptic tasks, focusing on haptic orientation, have been developed in order  
47 to explore haptic impairments in unilateral neglect (Gentaz *et al.*, 2002; Rousseaux *et al.*, 2015).  
48 To our knowledge, no information is available about whether haptic shape perception (or  
49 object-based perception) is perturbed in unilateral neglect. McIntosh *et al.*, (2002) performed a  
50 related study trying to investigate part of this question with a haptic spatial judgement in  
51 peripersonal space. In a blindfolded neglect patient, they used a haptic circle-centering task and  
52 found a rightward shift compared with the true centre (McIntosh *et al.*, 2002). However, this  
53 task can be viewed as a two-dimensional analogue of the visual bisection task, and the bias  
54 observed could be ascribed to the perception of either the shape or the size of the circle, to the  
55 computation of its centre, or to the proximal component of the pointing movement required to  
56 indicate the centre (Girardi *et al.*, 2004). The first aim of our study was therefore to specifically  
57 test for the existence of haptic neglect in right brain damaged patients, using a newly developed  
58 haptic shape discrimination task. In order to perform the task it is necessary to integrate  
59 information from the distal parts of the body touching the object with information about the  
60 position of the body segments in space. Thus, the task depends on spatio-temporal integration  
61 of tactile and kinaesthetic inputs (Gentaz *et al.*, 2008). This reconstructed representation of the  
62 stimulus shape could be impaired in neglect patients. We asked our patients to perform this task  
63 with their right healthy hand in order to exclude any primary somatosensory deficits, *e.g.* a  
64 tactile deficit, or motor deficits. Using the right hand, connected to the left hemisphere, we can  
65 ensure that any deficits can be attributed to impairment in high level processing of haptic signals,  
66 in particular spatial cognition functions located in the right hemisphere.

67 Twenty years ago, rehabilitation using Prism Adaptation (PA), a visuo-motor adaptation  
68 with glasses inducing a rightward optical deviation of the visual field and modifying visuomotor

69 transformations, was shown to improve unilateral neglect (Rossetti *et al.*, 1998) and related  
70 aspects of spatial cognition (Jacquin-Courtois *et al.*, 2013; Michel, 2016; Rossetti, Nijboer, &  
71 Kitazawa, 2019). Several studies using this bottom-up strategy have shown an improvement of  
72 hemispatial neglect in visuo-motor tasks, but also in non-motor and non-visual tasks, suggesting  
73 an expansion of prism adaptation to sensory, motor and cognitive systems (Rossetti *et al.*, 2004;  
74 Rode *et al.*, 1999; 2001; Tilikete *et al.*, 2001; Jacquin-Courtois *et al.*, 2010; Angeli *et al.*, 2004;  
75 Watanabe & Amimoto, 2010). The second aim of our study was to test whether this procedure,  
76 known to act on higher-level cognitive processes, could also improve haptic shape  
77 discrimination in neglect and right brain damaged patients without neglect.

78

## 79 Material and Methods

80

### 81 *Patients and right brain damaged controls*

82 Three consecutively enrolled right brain damaged patients with neglect (RBD+, 1 male  
83 and 2 females; 66, 38 and 70 years old) participated in this study. The inclusion criteria were:  
84 i) one cerebral lesion affecting the right parietal lobe; ii) left neglect; iii) absence of  
85 somatosensory deficits in the hands. Four consecutively-enrolled right brain damaged control  
86 patients without neglect (RBD-, 1 male and 3 females; 77, 72, 72 and 58 years old) were also  
87 included. All patients had no history or evidence of previous neurological or psychiatric  
88 disorders, or dementia. All patients were right handed as assessed with the Edinburgh  
89 Handedness Inventory (Oldfield, 1971), and gave their informed consent prior the study.

90 The presence of unilateral neglect was assessed using three different tests: i) a scene  
91 copying test adapted from Gainotti *et al.* (Gainotti *et al.*, 1972); ii) a star cancellation test  
92 (Wilson *et al.*, 1987); iii) a line bisection test where the patient had to mark the center of a 20  
93 cm line with a soft pen. The length of the left side of the line was measured to the nearest mm.  
94 Marks placed on the right of the true centre yielded positive values while those placed on the  
95 left yielded negative values. The inclusion criteria for neglect patients were: at least 2 items  
96 omitted in the left part of the drawing in the scene copying test; a rightward line bisection bias  
97 larger than 10 mm; and at least 5 omissions in the star cancellation test (Halligan *et al.*, 1990).

98 On the date of data collection all patients had been admitted to a neurological  
99 rehabilitation unit for treatment of left hemiplegia. Clinical features and CT-scan data are  
100 described in Table 1.

101 CT or MRI allowed us to map lesions of RBD patients. All patients showed a rather  
102 extensive unilateral lesion. Aetiology was always vascular, ischaemic in 4 cases and

103 haemorrhagic in the 3 other cases. The RBD<sup>+</sup> lesions were drawn on a standard MRI template  
104 with a 1-mm slice distance (voxels of 1mm<sup>3</sup>) using MRIcro software (Rorden and Brett, 2000,  
105 www.mricro.com). This procedure required us to adapt the standard template to each CT/MRI  
106 patient's orientation. Subsequently, each lesion was manually drawn on the corresponding  
107 adapted template and, finally backtranslated, in order to return to the parameters of the original  
108 MRI template. Figure 1 shows the lesions of each neglect patient, and the lesion overlap of the  
109 three RBD<sup>+</sup> patients as well as that of the four right RBD<sup>-</sup> patients. Overall, lesions were more  
110 extensive in the RBD<sup>+</sup> group (mean lesion volume 134.94cc $\pm$ 59.03; range 98.46-203.05cc)  
111 than in the RBD<sup>-</sup> group (mean lesion volume 50.75cc $\pm$ 53.21; range 2.23-119.37cc). This is  
112 in agreement with larger samples of patients (Hier *et al.*, 1983; Lebovitch *et al.*, 1998; Mancini  
113 *et al.*, 2011). In the RBD<sup>+</sup> group, the maximum overlap was in an area in the white matter on  
114 the right parietal lobe. In the RBD<sup>-</sup> group, the maximum overlap (in 3 out of 4) was more  
115 anterior, in the internal capsule and the lenticular nucleus.

116

### 117 *Neglect patient histories*

118 RBD<sup>+</sup>1, a 38 year-old woman, was admitted to a neurological unit for sudden right  
119 cervico-occipital cephalalgia. An MRI scan revealed a subarachnoid haemorrhage with fronto-  
120 parietal haematoma, and an aneurysm of the horizontal portion of right middle cerebral artery.  
121 After surgery, the patient had left hemiplegia and left visuo-spatial neglect, anosognosia, but  
122 no motor or sensory deficits in the left hemibody, nor sensory extinction.

123 RBD<sup>+</sup>2, a 66-year-old man, was hospitalized for a thrombosis of the central artery of the  
124 right retina, during surgery he had a stroke. A CT scan showed an ischaemic lesion of the right  
125 hemisphere leading to left hemiplegia and left visuo-spatial neglect. The patient did not show  
126 any motor or sensory deficits in the left hemibody. The patient exhibited auditory and visual  
127 extinction,

128 RBD<sup>+</sup>3, a 70 year-old woman, was admitted to the neurological unit for a sudden onset  
129 of left hemiplegia, left lateral homonymous hemianopia and left unilateral neglect. The CT scan  
130 revealed a right parieto-occipital haematoma inducing left neglect, left hemianopia,  
131 anosognosia, and constructive apraxia. The patient showed no tonic ocular nor cephalic  
132 deviation towards the right, no motor or sensory deficits in the left hemibody, nor sensory  
133 extinction.

134

### 135 *Experimental procedure*

136 The patient was seated in a comfortable chair with their right-hand resting on a table  
137 and was presented with pairs of objects. A wooden board placed in front of the patient in the  
138 midsagittal axis was used to present two objects (4.5 cm diameter; 0.8 cm height) with a 10 cm  
139 distance between the centres of each object (see figure 2A). A set of 19 different objects made  
140 of thick hard plastic, without any specific texture, was either made with holes or cut in pie shape  
141 (see figure 2B). The combination of objects within a pair followed three possible criteria: two  
142 identical objects, two objects with a difference on the left (*e.g.* C/A<sub>inverse</sub>, E<sub>inverse</sub>/F<sub>inverse</sub>,  
143 L/P...see also figure 2A bottom), two objects with a difference on the right (*e.g.*; A/C; E/F, L/E,  
144 P<sub>inverse</sub>/L... see also figure 2A bottom). Objects were randomly presented as followed:  
145 top/bottom and then bottom/top (each given object within a pair was presented once in the top  
146 position and once in the bottom position). Moreover, for each session and each patient the  
147 sequence of the pairs of objects were drawn at random. The blindfolded patient, without visual  
148 control performed a haptic discrimination task, had to fully explore the objects successively  
149 with his/her right hand. The exploration, performed with the right fingertips (see figure 2A),  
150 began either by the top or bottom object in a random order, without any instructed time  
151 constraint. The patients was allowed to go back and forth between the two objects. No reference  
152 was made to the fact that objects might differ on their left or on their right side. Following this  
153 haptic exploration they were requested to verbally report whether the objects were the same or  
154 different. This global question enabled the task to be performed without focusing on left vs right  
155 issues. The patient never received feedback during the test. The investigator visually ensured  
156 that the patient fully explored the objects by two means. First, direct vision of the patient's hand  
157 provided a top view perspective. Second, a surveillance camera was added to provide online  
158 monitoring of a front-view perspective on the hand and the objects. These were simultaneously  
159 displayed on a screen viewed by the experimenter allowing a qualitative assessment of hand  
160 movement exploration. As our objects were small and aligned with the midsagittal plane (see  
161 figure 2A top) no left object exploration deficit was expected because previous studies revealed  
162 a partial exploration on the left hemispace in RBD+ (Karnath and Fetter, 1992; de Renzi *et al.*,  
163 1970). This haptic discrimination task was performed twice in two pre-test sessions lasting  
164 approximately 45 minutes each, and two days apart. During each session 65 object-pairs were  
165 presented, 12 with holes and 53 with pie shapes. In 19 trials, objects were identical, while in  
166 the other 46 differences existed either in the left-half side (*e.g.* C/A<sub>inverse</sub>, E<sub>inverse</sub>/F<sub>inverse</sub>,  
167 L/P...see also figure 2A) or in the right-half side (*e.g.* A/C; E/F, L/E, P<sub>inverse</sub>/L... see also figure  
168 2A). Two days later, a prism adaptation session was administered to the patients. During this  
169 period, the subject's head was stabilized in a chin rest, and he/she wore a pair of goggles fitted

170 with wide-field point-to-point lenses inducing a 10° rightward shift of the visual field. The  
171 prisms covered a total visual field of 105% in which each monocular field represented 75°,  
172 while the central visual binocular field represented 45° (Optique Peter®, Lyon, France). During  
173 prism adaptation (PA), patients were requested to point, with fast but comfortable movements  
174 with their right hand towards a visual dot, located either to the right or the left of the body  
175 midline (10° eccentricity). Fifty pointing movements (i.e. about 2 to 5 minutes) were performed  
176 in a pseudo-randomized order towards the two dots (details in Rossetti *et al.*, 1998 or Rode *et*  
177 *al.*, 2015). Then the prism glasses were removed. The patient was first asked to point straight-  
178 ahead in order to verify the presence of after-effects. We ensured that a minimal 5cm shift was  
179 observed between the pre and the post test of adaptation. Then the post-test was performed  
180 using the same haptic discrimination task and the same verbal description as during pre-tests.

181 For each haptic discrimination trial, correct responses were given a value of 1 and errors  
182 0. For each session, error rates (left half errors and right half errors) were computed as a  
183 percentage of the total number of objects explored by each patient. Statistical analyses were  
184 conducted with Statistica® 13.1 using non-parametric tests (Mann-Whitney U-test). This  
185 statistical analysis was designed to address three main questions: i) are patient's performances  
186 different in the two pre-test? ii) does our haptic shape discrimination task detect haptic neglect?  
187 iii) does PA improve haptic shape discrimination in unilateral neglect?

188

## 189 Results

190

191 Qualitative analysis of hand exploration during each test (Pre1, Pre2 and Post PA),  
192 monitored by the investigator, revealed no exploration deficit in RBD+ or RBD- patients. Over  
193 all patients, errors made for identical objects represented less than 1% of the trials. As they were  
194 not informative about left-right asymmetry judgements, they were discarded from further  
195 analyses.

196 First, raw data and means for each patient's population and for the two pre-test were  
197 reported in figure 3. Left and Right error rates were stable across the two pre-test sessions in  
198 RBD+ (Left error rate 25.5 and 23.6 for Pre1 and Pre2 respectively; Mann-Whitney U-test;  
199  $Z=0.80$ ,  $p=0.42$ ; Right error rate 10.8 and 10.3 for Pre1 and Pre2 respectively; Mann-Whitney  
200 U-test;  $Z=0.44$ ,  $p=0.65$ ). Stability of results was also observed across the two pre-test sessions  
201 for RBD- (Left error rate 14.6 and 13.0 for Pre1 and Pre2 respectively; Mann-Whitney U-test;  
202  $Z=0.73$ ,  $p=0.47$ ; Right error rate 12.0 and 8.3 for Pre1 and Pre2 respectively; Mann-Whitney  
203 U-test;  $Z=1.46$ ,  $p=0.14$ ) suggesting test reliability.

204

205 Second, the tactile shape discrimination leads to distinct haptic impairments in patients.  
206 The largest effect was a substantial increase in left error rates (as much as 76%) for RBD+  
207 patients (Mann-Whitney U-test;  $Z=1.98$ ,  $p<0.05$ ), whereas they behaved like RBD- for the right  
208 side differences (Mann-Whitney U-test;  $Z=0.53$ ,  $p=0.60$ ). Unlike RBD+, RBD- patient error  
209 rates were evenly distributed across the left and right sides (see Figure 3), suggesting that our  
210 shape discrimination task can diagnose haptic neglect.

211 Third, figure 4 shows performance with left as well as right error rates before (Pre1 and  
212 Pre2) and after PA for RBD+ and RBD-. After PA, a substantial decrease in left error rates in  
213 RBD+ (minus 18%, *i.e.* a relative drop of about 80%) was observed along with a slight decrease  
214 (minus 7%) in RBD-. Performance for both groups were no longer statistically different (Mann-  
215 Whitney U-test;  $Z=0.18$ ,  $p=0.85$ ) suggesting that RBD+ performances improved to the control  
216 level. For the right error rates, RBD+ exhibited a reduction of about 9% while the decrease of  
217 about 5% in RBD- without any statistical difference (Mann-Whitney U-test;  $Z=0.88$ ,  $p=0.38$ ).  
218

## 219 Discussion

220 The aim of our study was to assess haptic shape discrimination in right brain damaged  
221 patients with or without neglect and to examine the effect of prism adaptation on this task. Our  
222 study provides two main new findings. First, three consecutively, included neglect patients  
223 exhibited a clearly asymmetric disturbance for haptic shape discrimination, which suggests that  
224 haptic neglect may be a common feature in these patients. Second, our results show that prism  
225 adaptation can improve haptic discrimination in left neglect patients. In addition, we observe  
226 that improvement, although milder, is also observed for right-brain-damaged patients without  
227 neglect.

228 Although often thought of as a primarily visual disorder, other sensory modalities, such  
229 as somatosensory information, can be also affected (review in Brozzoli *et al.*, 2006). In our  
230 original haptic shape discrimination task, patients were asked to evaluate, using their right hand,  
231 whether two objects were similar or not, without having to identify them. The error rates were  
232 above 10% in right brain damage patients without neglect. The striking result was a  
233 substantially higher error rate when differences between objects were on the left-hand side of  
234 the objects, up to as much as 76% for these basic shapes, in neglect patients only. Thus,  
235 analogous to results found in numerous visual tests in spatial neglect patients (review in  
236 Jacquin-Courtois *et al.*, 2013, Rode *et al.*, 2017) a marked lateralized impairment for haptic  
237 discrimination was observed. Perception of the spatial properties of an object always involves

238 exploratory movements, depending on the specificity of the touched object (Lederman &  
239 Klatsky, 1987). As the haptic system relies on contact between the fingers and the object, one  
240 could speculate that our results were due to a tactile misperception, as tactile deficits have been  
241 found in neglect patients (*e.g.* Maravita *et al.*, 2004, Dijkerman *et al.*, 2003). However, our task  
242 was performed with the right hand, for which tactile perception remains unimpaired (Maravita  
243 *et al.*, 2004) due to the integration of the somatosensory inputs in the healthy left hemisphere.  
244 Previous studies investigating eye or hand exploratory movements revealed a partially left space  
245 exploration in RBD+ (Karnath and Fetter, 1995; De Renzi *et al.*, 1970; McIntosh *et al.*, 2002;  
246 Revol 2000). As our haptic-task discrimination task was very close to the sagittal plane, no  
247 incomplete object exploration was expected, and nor was it observed. Moreover, our patients  
248 were blindfolded, preventing visual cueing effects, known to affect performance (Riddoch &  
249 Humphreys, 1983), and thought to be responsible for the rightward bias in the haptic exploration  
250 maze test (De Renzi *et al.*, 1970). Taken as a whole, it is unlikely that a disruption of basic  
251 sensory-motor mechanisms subserving object exploration account for our results.

252         Since clinical manifestations are observable in non-visual tasks neglect has long been  
253 considered as a higher-order disorder of spatial cognition (Bisiach *et al.*, 1981; Rode *et al.*, 2017).  
254 The comparison of the two objects entails a spatio-temporal integration of kinaesthetic and  
255 tactile inputs generating a representation of the stimulus (Gentaz *et al.*, 2008). Previous studies  
256 have shown that neglect patients often exhibit representational neglect: a failure to report details  
257 from the left side of mentally visualized images (Bisiach & Luzatti, 1978; Rode *et al.*, 2007).  
258 One cannot exclude that the observed haptic spatial orientation deficits (Gentaz *et al.*, 2002;  
259 Kerkhoff, 1999, Utz *al.*, 2011) could also be due to a mental imagery deficit. Therefore, an  
260 impairment of high level processing of haptic signals leading to a mental representation of the  
261 stimulus, *i.e.* a spatial cognition function known to occur in the right hemisphere, may also be  
262 responsible for haptic shape discrimination deficits. Further investigations should explore  
263 whether the haptic deficit is correlated with a mental imagery deficit and whether this imagery  
264 is visual.

265         The parietal cortex is a multimodal area related to space representation (Huang & Serino,  
266 2018) and orientation of spatial behaviour (Jeannerod, 1988) essential for haptic shape  
267 processing. Recent fMRI studies revealed an activation of the right parietal lobe when healthy  
268 subjects were asked to perform a haptic perception task (Van Boven *et al.*, 2005; Masson *et al.*,  
269 2016). The overlapping lesion site in the parietal cortex in our three neglect patients seems  
270 compatible with these results. However, as expected, our RDB+ patients tend to have larger  
271 lesions than RDB- patients (Hier *et al.*, 1983; Leibovitch *et al.*, 1998; Mancini *et al.*, 2011), and

272 they also actually perform worse. Further studies with larger patient samples should specifically  
273 address this issue and investigate the potential relationship between lesion site and/or size and  
274 haptic deficits.

275 Finally, this haptic shape discrimination test appears to be reliable for assessing haptic  
276 neglect with a left/right error rates asymmetry, as well as a haptic deficit in RBD patients  
277 without neglect but with symmetrical error rates. This haptic test provides further support for  
278 the argument suggesting that spatial neglect is a multisensory deficit (review in Jacobs *et al.*,  
279 2012). Another new finding in the present study is that prism adaptation induced a clear  
280 improvement in haptic neglect, with a substantial decrease of left error rates representing a  
281 relative drop of about 80%. As discussed above regarding the two pre-test sessions, visual  
282 control of exploratory movements failed to reveal any asymmetrical exploration movements or  
283 over-exploration of the left side of the object, ensuring that the circumference and the surface  
284 of the object was fully explored before the verbal response was made. In the RBD- group,  
285 performance was already close to normal in the two pre-test sessions, making it difficult to  
286 observe substantial improvement after PA. Our data show that initially impaired RBD+  
287 performance reached control levels, *i.e.* RBD- performance, after PA. This further demonstrates  
288 that prism adaptation can improve shape processing in a non-exposed modality. We cannot  
289 exclude that a practise effect may potentially contribute to the pattern of results observed here  
290 as the patients performed the task for the third time. The influence of practice was, however,  
291 minimized by using a sequence of random pairs of object for each session and each patient.  
292 Furthermore, performance varied by less than 3% between the two pre-test sessions while it  
293 reached a magnitude of 15% between the second and third haptic tests in RBD+. To date, the  
294 few studies investigating the effect of PA on tactile manifestations of neglect have shown an  
295 improvement in the left hand of tactile extinction (*e.g.* Maravita *et al.*, 2003, Serino *et al.*, 2007),  
296 pressure sensitivity and proprioception (Dijkerman *et al.*, 2004). Positive results of PA on a  
297 haptic spatial judgement task have also been found both in a chronic neglect patient (McIntosh  
298 *et al.*, 2002) and in healthy subjects (Girardi *et al.*, 2004), suggesting that PA affects higher  
299 cognitive functions. Due to a uniform shift of the visual field, prism exposure is supposed to  
300 manipulate the body-space interface in egocentric coordinates, as evidenced by the after effects  
301 with a leftward shift in the straight ahead pointing tasks (Rossetti *et al.*, 1998, Sarri *et al.*, 2008).  
302 In our haptic discrimination task one can postulate that objects must be compared one to another  
303 using an object-centred frame of reference, which is affected in RBD+ (Ota *et al.*, 2001), and  
304 which can also be influenced by PA treatment. It remains to be explained how such egocentric  
305 manipulation may alter object-centred perception of shape in the haptic domain, knowing that

306 some visual object-centred tasks appear not be improved by PA (Sarri *et al.*, 2006). In our  
307 experimental design, these two frames of reference may be confused, because objects are  
308 aligned in the midsagittal plane. Therefore the impairment of high-level processing of haptic  
309 signals can be linked either to a deficit of space representation (Bisiach & Luzzatti, 1978; Rode  
310 *et al.*, 2001), or to a deficit of object representation (*e.g.* Ota *et al.*, 2001). Further studies should  
311 address this issue, for example, by placing the object in different space locations. It is also worth  
312 noting that we observed a milder improvement in right brain damaged patients without neglect,  
313 suggesting that the cognitive effect of PA is not restricted to patients with unilateral neglect  
314 (Tilikete *et al.*, 2001; Sumitani *et al.*, 2007; Jacquin-Courtois *et al.*, 2017), in accordance with  
315 previously reported results in healthy subjects (Colent *et al.*, 2000; Berberovic & Mattingley,  
316 2003; Girardi *et al.*, 2004). Finally, the slight improvement on the right error rates in all right  
317 brain damaged patients suggests that PA enlarges the mapping of space not only on the left side,  
318 but also on the right side, as has already been described for visual imagery (Rode *et al.*, 2001).

319 Numerous studies have shown that PA improves visuo-motor, non-motor, and also non-  
320 visual tasks in unilateral neglect suggesting an expansion of PA to spatial cognition (review in  
321 Jacquin *et al.*, 2013, Rode *et al.*, 2017). This “bottom-up” rehabilitation, which bypasses central  
322 awareness of the deficit, might influence higher-level supramodal representations associated  
323 with spatial attention rather than being limited to low-level sensori-motor re-mapping.  
324 Moreover, this procedure seems to interact with higher other brain functions related to  
325 multisensory integration and can have beneficial effects on sensory processing in different  
326 modalities, supporting the hypothesis of cross-modal central effects. This intersensory  
327 generalization of PA effects calls for further research in order to explore the mechanisms of  
328 transfer and expansion to unexposed tasks.

329  
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334

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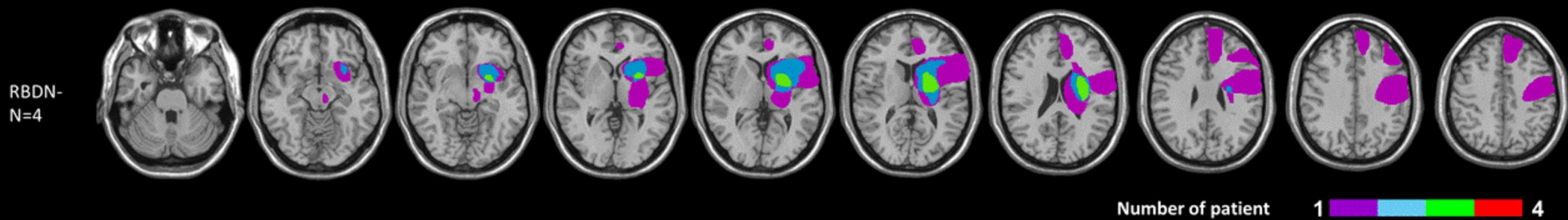
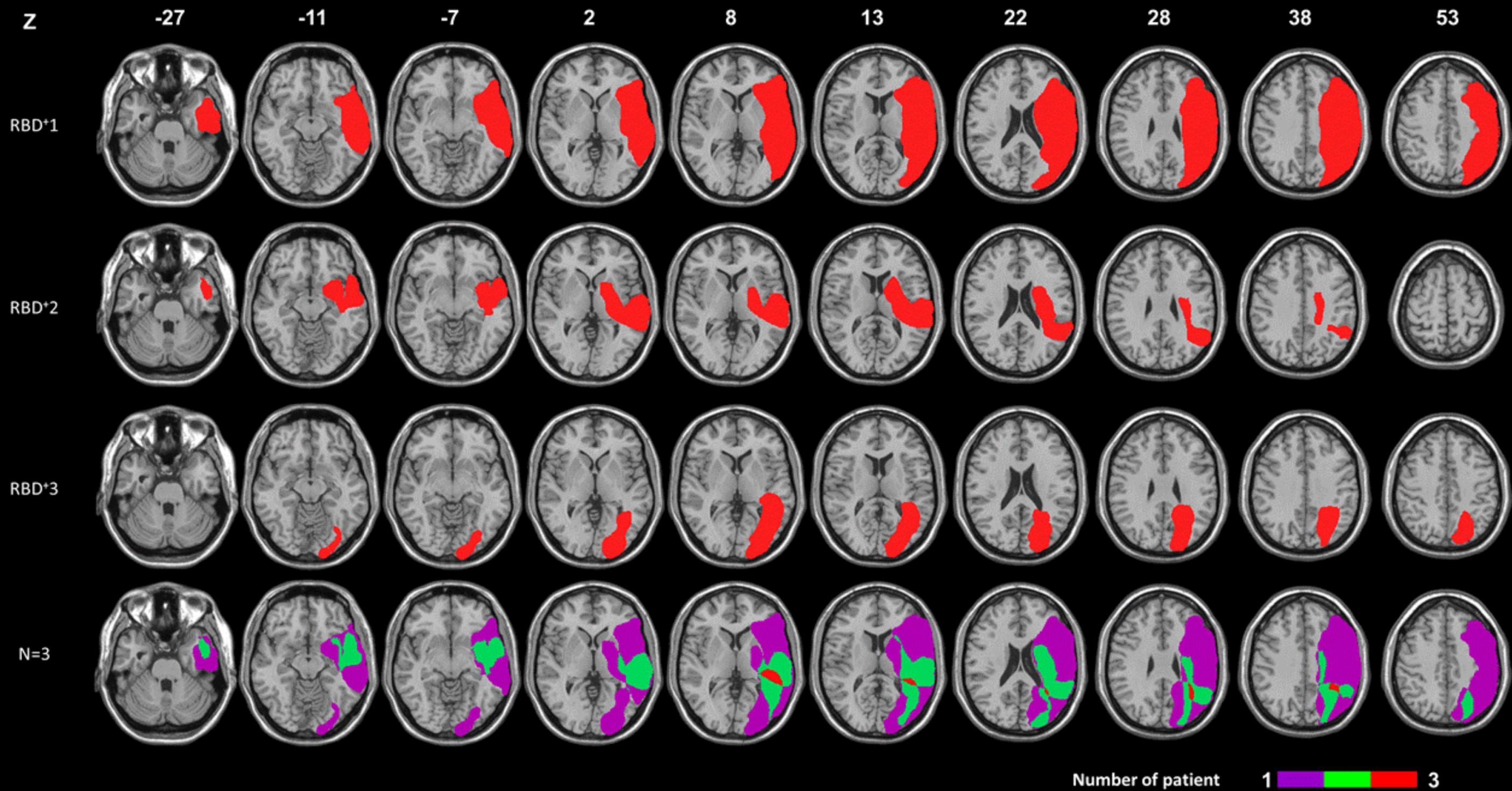
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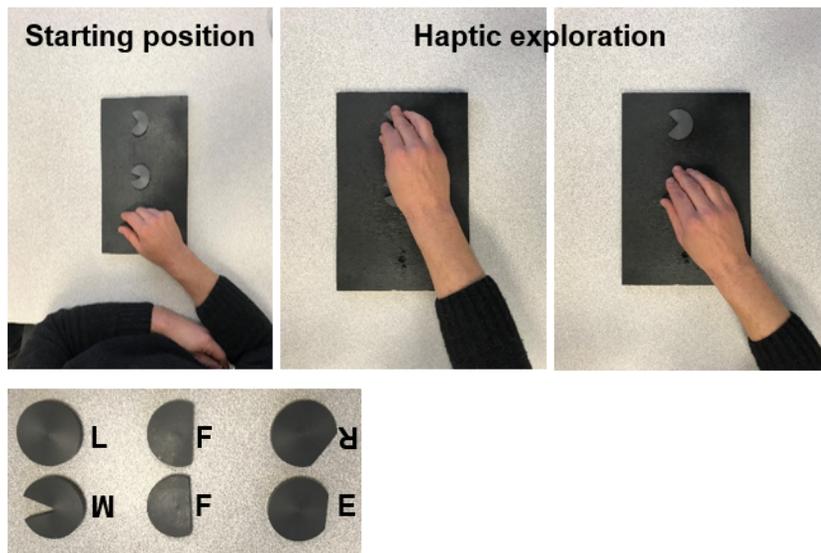
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B

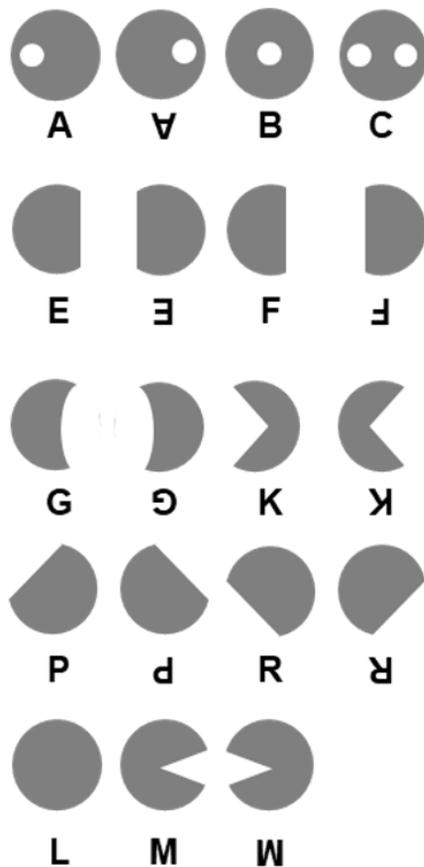


Figure 3

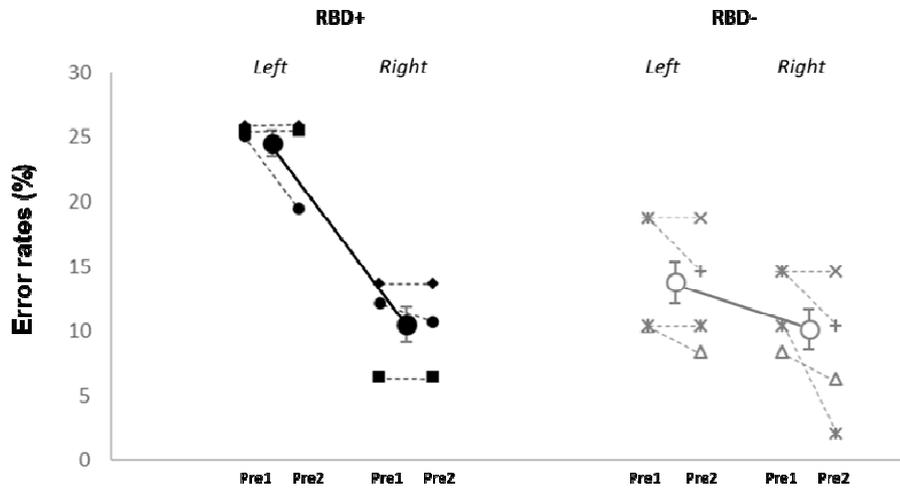
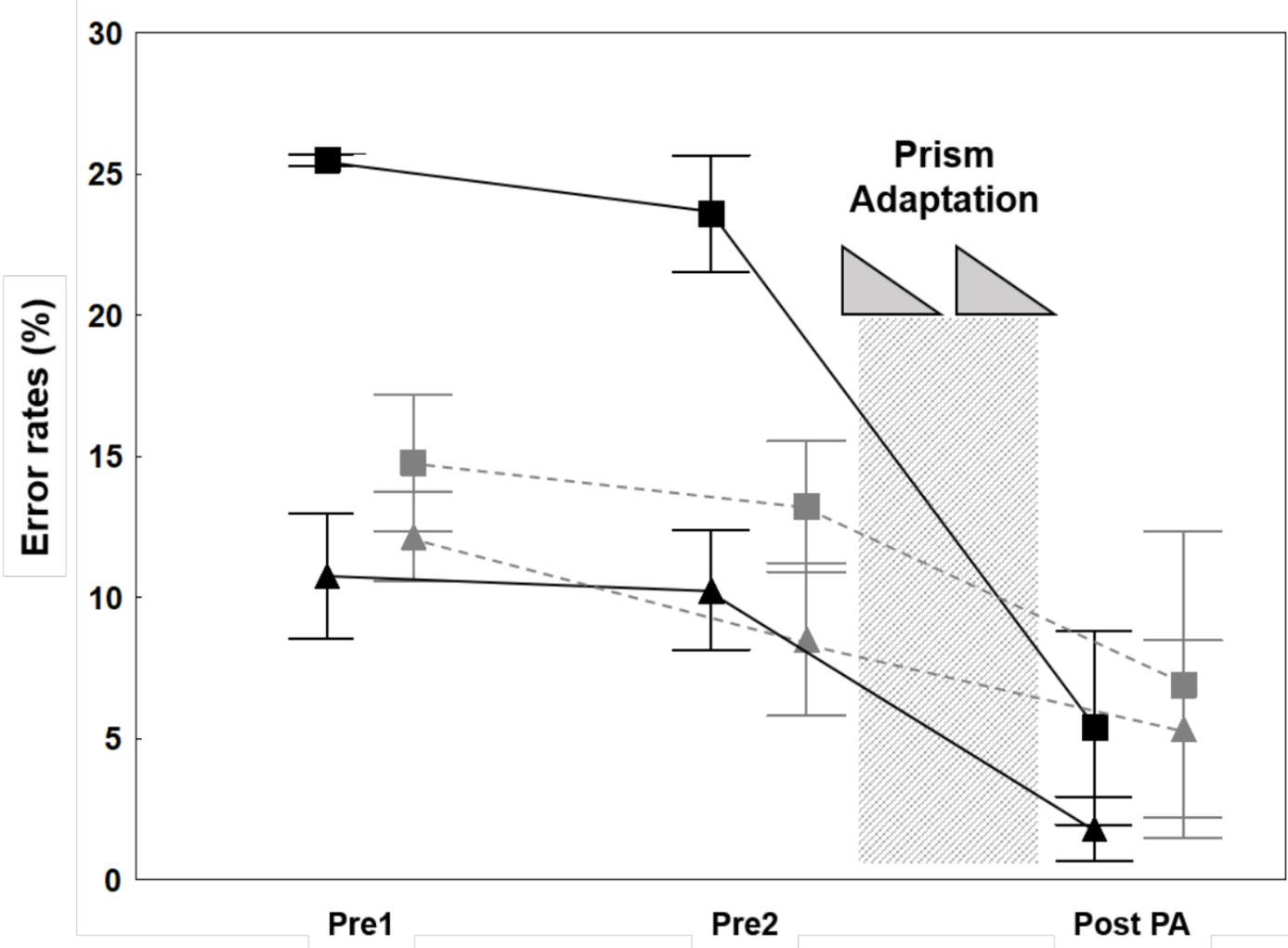


Figure 3: Raw error rates and mean (%)  $\pm$  SEM, in the haptic test performed by RBD+ (black) and RBD- (grey) in the two pre-test sessions (Pre1 and Pre2). **Left and Right refer to the sides of the object.** A huge increase of left side errors is visible in RBD+, who produced more than 120% more errors on the left as compared to the right, whereas in RBD- this ratio was only 30%.



<b>Patients</b>	<b>Gender/Age</b>	<b>Lesion</b>	<b>Etiology</b>	<b>Days post stroke</b>	<b>LHH</b>	<b>Gainotti drawing</b>	<b>Star cancellation test omissions</b>	<b>Line bisection in mm</b>
RBD+1	Female/38	Fronto-Parietal	Haemorrhagic	30	n	2	15**	19
RBD+2	male/66	Parietal-lenticular	Ischemia	31	n.a	3	11**, 2*	24
RBD+3	female/70	Parieto-Occipital	Haemorrhagic	30	y	2	7**, 2*	62
RBD-1	female/72	Capsulo-lenticular	Haemorrhagic	32	n	5	0	-10
RBD-2	female/72	Pontic infarct paramedian	Ischemia	35	n	5	0	12
RBD-3	female/58	Fronto-Parietal	Ischemia	28	n	4	1**, 1*	5
RBD-4	male/77	Capsulo-lenticular-cingular gyrus	Ischemia	31	n	5	2**, 2*	9