

# The space of senses: impaired crossmodal interactions in a patient with Balint syndrome after bilateral parietal damage

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## Abstract

Balint syndrome after bilateral parietal damage involves a severe disturbance of space representation including impaired oculomotor behaviour, optic ataxia, and simultanagnosia. Binding of object features into a unique spatial representation can also be impaired. We report a patient with bilateral parietal lesions and Balint syndrome, showing severe spatial deficits in several visual tasks predominantly affecting the left hemispace. In particular, we tested whether a loss of spatial representation would affect crossmodal interactions between simultaneous visual and tactile events occurring at the same versus different locations. A tactile discrimination task, where spatially congruent or incongruent visual cues were delivered near the patient's hands, was used. Following stimulation of the left hand in the left side of space, we observed visuo-tactile interactions that were not modulated by spatially congruent conditions. In contrast, performance following stimulation of the right hand in the right side of space was affected in a spatially selective manner—facilitated for congruent stimuli and slowed for incongruent stimuli. To dissociate effects on somatotopic and spatiotopic coordinates, we crossed the patient's hands during unimodal tactile discriminations. Tactile performance of the left hand improved when it was positioned in the right hemispace, whereas placing the right hand in left space produced no significant changes, suggesting that left-sided tactile inputs are coded with respect to a combination of limb- and trunk-centred coordinates. These data converge with recent findings in animals and healthy humans to indicate a critical role of the posterior parietal cortex in multimodal spatial integration, and in the fusion of different coordinates into a unified representation of space.

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## 1. Introduction

Balint syndrome follows from bilateral lesions of the parietal lobe and is characterized by three main clinical signs: gaze apraxia, simultanagnosia, and optic ataxia (Balint, 1909). It has been argued that Balint syndrome involves a dramatic impairment in space representation, while visual processing of basic perceptual features such as colour and form is spared (e.g., Friedman-Hill, Robertson, & Treisman, 1995), although spatial problems in perception and visually guided action are likely to reflect distinct underlying disorders (e.g., see Milner et al., 1999). Most studies of spatial

disturbances affecting visual perception in Balint patients have focused on their severe deficit in localising objects and in binding multiple features into single objects. Thus, these patients may show erroneous combinations of visual features (e.g., shape and colour) that belong to distinct objects, resulting in “illusory conjunctions” (Friedman-Hill et al., 1995; Phan, Schendel, Recanzone, & Robertson, 2000; Robertson, Treisman, Friedman-Hill, & Grabowecky, 1997). According to Treisman (Treisman, 1988; Treisman & Gelade, 1980), such binding critically depends on the correct mapping of distinct perceptual features into a common representation of spatial location, an ability hypothesized to rely on parietal cortex.

Whereas the binding of sensory features has been mainly investigated in unisensory situations (e.g., in vision), there is increasing evidence that spatial processes may also operate

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to integrate multisensory features—e.g., touch and vision (Grefkes, Weiss, Zilles, & Fink, 2002), or audition and vision (Bushara et al., 2003; Dolan, Morris, & de Gelder, 2001)—based on some common map of locations. This crossmodal integration of different sensory inputs is also thought to depend on a supramodal representation of space subserved by parietal cortical areas (Andersen, Snyder, Bradley, & Xing, 1997). In particular, studies in healthy subjects have revealed strong crossmodal links in perception and in spatial attention (Spence, 2002), by showing that distinct multimodal events that are spatially close may influence each other. Thus, discriminative judgments for events in a given modality are more rapid when accompanied by a spatially predictive cue in another modality (crossmodal cueing; see Spence, 2002 for a review). Such crossmodal links have been demonstrated between visual, tactile, auditory and olfactory modalities. In line with this, a role of parietal cortex in crossmodal spatial interactions has been supported by neurophysiological studies in monkeys (Andersen et al., 1997; Obayashi, Tanaka, & Iriki, 2000) and functional imaging in healthy humans (Bremmer, Schlack, Duhamel, Graf, & Fink, 2001), as well as by the finding of crossmodal extinction in neglect patients after right parietal lesions (Di Pellegrino, Ládavas, & Farné, 1997; Maravita, Spence, & Driver, 2003). However, a previous study using auditory-visual stimuli during a localization task in a patient with Balint syndrome (Phan et al., 2000) showed that multisensory stimuli may be bound together prior to parietal areas, although explicit perception and/or localization of the bound stimulus might critically depend on parietal cortex.

Here we describe the effects of bilateral parietal damage on crossmodal interactions in a patient with Balint syndrome, using a spatial cueing paradigm that did not require explicit localization of the stimuli. We asked whether a severe impairment in space representation caused by bilateral parietal damage would also impair crossmodal links for multisensory events. We tested crossmodal spatial interactions during a visual-tactile discrimination task, where spatially congruent or non-congruent visual cues were delivered simultaneously with tactile stimuli. Our hypothesis was that the severe loss in spatial coding associated with Balint syndrome might result in a loss of the facilitation normally produced by a spatial congruency between simultaneous tactile and visual events (or correspondingly, a loss of any interference produced by spatial incongruency).

## 2. Case history

MC, a right-handed 48 year-old woman, was admitted to hospital in August 2002 with severe headache due to a posterior subarachnoid haemorrhage, extending into the third and fourth ventricles. An initial MRI scan showed no brain lesion. Surgical removal of the blood was done shortly after admission. No vascular malformation or aneurysm was found. During the following days, MC presented with a cor-

tical blindness due to secondary vasospasm and bilateral parieto-occipital ischemia, which rapidly recovered. However, the patient showed persisting signs of bilateral parietal dysfunction, i.e. severe optic ataxia, gaze apraxia and simultanagnosia (Balint syndrome) together with left–right disorientation, finger agnosia and dyscalculia (partial Gerstmann syndrome). Neurological examination showed only a partial defect of the left inferior visual field, but no motor or sensory deficits on either side. Somatosensory perception was preserved on both sides for touch, temperature, vibration, and position sense, and object recognition by palpation was normal. However, she showed tactile extinction during bilateral simultaneous touches, with a predominance of misses on the left relative to the right side.

In the visual domain, MC showed good capacities in object identification when objects were presented alone, but overlapping objects (e.g., Poppelreuter test) could not be properly identified. Counting of visual dots was severely impaired, even for small numbers of items. Line bisection and cancellation tasks were impossible due to severe optic ataxia. Face recognition was normal. Single-word reading was preserved, but text reading was severely impaired. Writing revealed severe spatial dysgraphia. Oral speech and ideomotor praxis were normal.

A brain MRI performed 3 months post-stroke revealed damage in the dorsal part of the left parietal cortex and in the inferior parietal cortex of the right hemisphere (Fig. 1). Lesions were larger in the right than left hemisphere. Detailed neuropsychological testing performed at the time of our experiments (4 months post-stroke) revealed persisting difficulties in several tasks assessing visual-spatial abilities (Table 1), including judgement of line orientation (Benton, Hamsher, Varney, & Spreen, 1983), copying the Rey Complex Figure (Osterrieth, 1944), spatial subtests of the Visual Object and Space Perception Battery (Warrington & James, 1991), line bisection, and Bell cancellation (Gauthier, Dehaut, & Joanette, 1989). In addition, MC showed spatial dyscalculia and spatial dysgraphia (with numbers and letters severely misaligned during writing or copying), spatial dyslexia (numerous omissions of words on both the left and right side of a text, with marked slowness during reading), as well as optic ataxia (see next section for more details). By contrast, her perception of shapes and colours was entirely preserved. Visual object recognition was normal in subtests of the Visual Object and Space Perception Battery (Warrington & James, 1991), as was her tactile object recognition. Evaluation of executive functions revealed mildly defective performance in verbal inhibition on a Stroop test (Spreen & Strauss, 1991), whereas verbal fluency was within the normal range. Spontaneous speech, picture naming and oral comprehension were normal but verbal reasoning (Information, Vocabulary and Similarities of the WAIS-R (Wechsler, 1987)) was relatively poor. Arithmetic skills were normal (WAIS-R). Verbal learning functions (Rey, 1958) were within the normal range, but delayed recall was moderately defective. In summary, MC

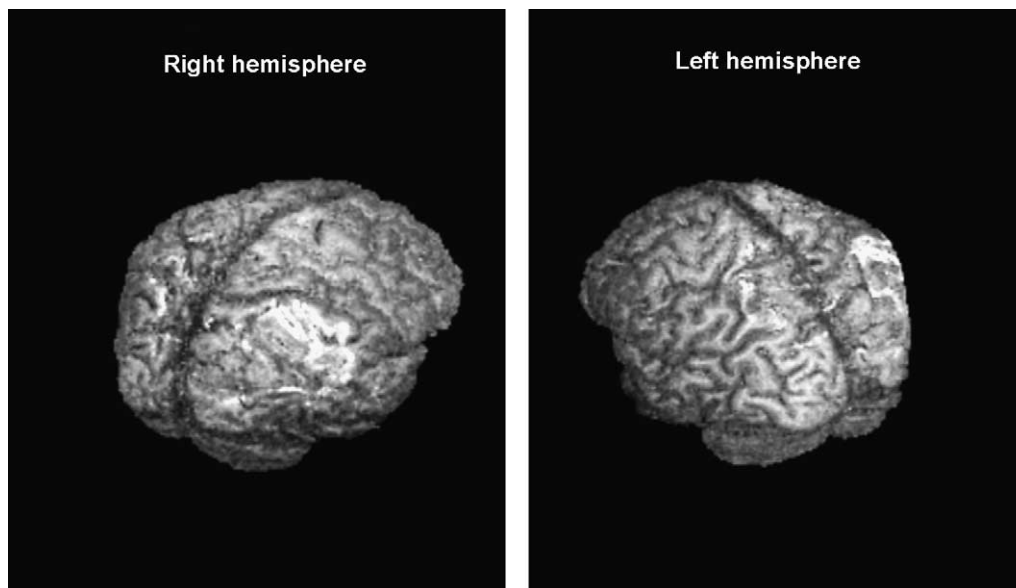


Fig. 1. Structural MRI performed 12 weeks post-stroke showed a parieto-occipital lesion in the right hemisphere and a lesion of the dorsolateral portion of the parietal lobe in the left hemisphere. The lesion was more extended and more posterior in the right than in the left hemisphere. Note that primary somatosensory cortex in the post-central gyrus was spared on both sides, consistent with a lack of clinical tactile deficit in the patient.

was severely impaired in many spatial tasks depending on right or left parietal lobe functions, whereas her perceptual visual recognition abilities were still remarkably spared, with only a moderate additional deficit in verbal recall and abstract verbal tasks (see Table 1).

### 2.1. Experiment series 1: general assessment of spatial deficits in visual tasks

Prior to testing of crossmodal spatial interactions, we sought to characterize the extent of our patient's disorder in spatial attention and spatial behaviour in a series of elementary visual tasks.

#### 2.1.1. Optic ataxia

**2.1.1.1. Method.** MC was asked to make rapid manual pointing movements to four visual targets located at a distance of 33 cm from her body, either aligned or deviated 30° or 60° to the left or right of the midline, while she fixated a central point on the midline (10 trials per location, 40 total). The starting point was a black dot located 10 cm in front of the patient on the midsagittal line of her body. Performance was registered by manually placing a mark at the movement end-point on a paper sheet (non visible to the patient). Distance errors (in cm) were measured at the end of the experiment for each target location (using a ruler). The same task was also given to a group of four healthy age-matched controls (three female, mean age 48.7).

**2.1.1.2. Results.** MC made severe pointing errors, typically deviating several centimetres away from the target (see Fig. 2). These errors occurred at all locations on both sides

of space (mean 8 cm) and were worse on the left than right side (12.4 cm versus 3.2 cm, respectively), whereas healthy subjects made only mild deviations that were symmetrical on both sides (mean 1.6 cm; 95% confidence interval = 1.45–1.75). MC's pointing was less accurate than controls at all locations, although clearly much more impaired on the left side. An ANOVA on the magnitude of her errors confirmed a significantly greater deficit in left versus right space ( $F = 38.72$ ,  $P < 0.001$ ). There was also a main effect of hand, since pointing with the left hand was significantly worse than with the right hand (mean error: 9.4 cm versus 6.2 cm, respectively;  $F = 4.73$ ,  $P = 0.036$ ), but the interaction hand X visual space was not significant ( $P = 0.14$ ). Healthy controls did not perform worse with their left hand, but typically showed an interaction between hand and space, with worse pointing of the right hand in left space and vice versa. We also note that in MC, pointing errors did not increase for the more peripheral locations as observed in healthy controls (see Fig. 2b) and other patients with optic ataxia (e.g., Milner et al., 2003), perhaps because eccentric targets were placed closer and lower in the visual field, where pointing performance is often better (Danckert & Goodale, 2001). More critically, however, these data demonstrate a severe and bilateral spatial disturbance of visuo-motor function in our patient, but with a clear predominance for left space and the left hand.

#### 2.1.2. Visual search

**2.1.2.1. Method.** To probe spatial visual attention in MC, she was asked to search for a simple visual target defined by colour, in the presence or absence of distracters. On each trial, the target (a green or a red dot, presented on white

Table 1  
Neuropsychological assessment

Tests	Score	
Visual-spatial abilities		
Judgement of line orientation test (Benton et al., 1983)	13 correct responses	Moderately impaired
Visual Object and Space Perception Battery (Warrington & James, 1991)		
Object perception		
Screening test	20/20	Cut-off: 16
Incomplete letters	18/20	Cut-off: 17
Silhouettes	19/30	Cut-off: 16
Object decision	16/20	Cut-off: 14
Progressive silhouettes	13/20	Cut-off: 14
Space perception		
Dot counting	5/10	Cut-off: 8
Position discrimination	10/20	Cut-off: 18
Number location	1/10	Cut-off: 7
Cube analysis	4/10	Cut-off: 6
Color matching	20/20	Within normal range
Bell's Cancellation Test (Gauthier et al., 1989)	4 left-sided omissions 0 right-sided omissions	Cut-off: left–right difference: 3
Executive functions		
Stroop test (Spreen & Strauss, 1991)		
Name color of dots (D)	25 in.	$m = 12.16 \pm 1.96$ in.
Name color print of non-color words (W)	20 in.	$m = 14.82 \pm 2.46$ in.
Name color print of color words (C)	70 in.	$m = 27.2 \pm 8.15$ in.
	4 errors	$m = 0.78 \pm 0.88$ in.
Interference score (C/D)	2.8	$m = 2.28 \pm 0.73$ in.
Verbal fluency (Cardebat, Doyon, Puel, Goulet, & Joannette, 1990)	27 productions	$m = 27 \pm 8$ in.
Verbal memory, 15 words (Rey, 1958)		
Learning	45	Cut-off: 44
Delayed recall	9	Cut-off: 10
General intellectual efficiency, Wechsler Adult Intelligence Scale-Revised (Wechsler, 1987)		
Arithmetic	7 pts	Percentile 9
Information	5 pts	Percentile 1
Vocabulary	14 pts	Percentile 2
Similarities	4 pts	Percentile 2
Comprehension	10 pts	Percentile 5

background) appeared either alone (no distracter condition) or among other black dots (distracter condition, with a fixed set size,  $n = 16$ ; all dots' size  $\sim 0.75^\circ$  visual angle). The location of targets and distracters was randomly distributed on the screen (17 in. wide), across an imaginary grid of  $4 \times 6$  positions, and varied from trial to trial. Targets appeared in either the left (50% of trials) or right (50% of trials) visual field. The patient had to report the target's colour (red or green) as quickly as possible. All stimuli remained on the screen until the response. RTs were measured by a key-press by the examiner as soon as the patient responded. Although such measures of RTs might increase variance, this would likely only mask differences between conditions, and it still allowed us to establish the relative effects of distracter number in controls as well as differences between visual fields in the patient. MC's performance for targets presented in each visual field and each distracter condition was compared to that of five age-matched controls.

**2.1.2.2. Results.** MC showed longer RTs for detecting targets than controls in both visual fields, but was more impaired for left- than right-side targets (2027 ms versus 1720 ms, respectively;  $F = 12.4$ ,  $P < 0.001$ ). Control subjects showed no asymmetry between left and right targets (mean RTs: 1642 ms versus 1604 ms, respectively;  $F = 0.63$ ,  $P = 0.44$ ). In addition, visual search in MC was not significantly affected by the presence of distracters (mean RT: 1784 ms without distracter versus 1962 ms with distracters;  $F = 1.79$ ,  $P = 0.18$ ), whereas control subjects showed a consistent slowing due to distracters (mean RT: 1560 ms versus 1685 ms;  $F = 26.1$ ,  $P < 0.001$ ). However, this difference in the patient was large and in the expected direction. Although performance in MC was particularly poor on the left side in the presence of distracters, the interaction between target side and distracters was not significant in her ( $F = 2.65$ ,  $P = 0.11$ ) or in controls ( $F = 0.04$ ,  $P = 0.98$ ). This pattern was confirmed by individual analyses showing a reliable cost of distracters in each control (unpaired  $t$ -test, all

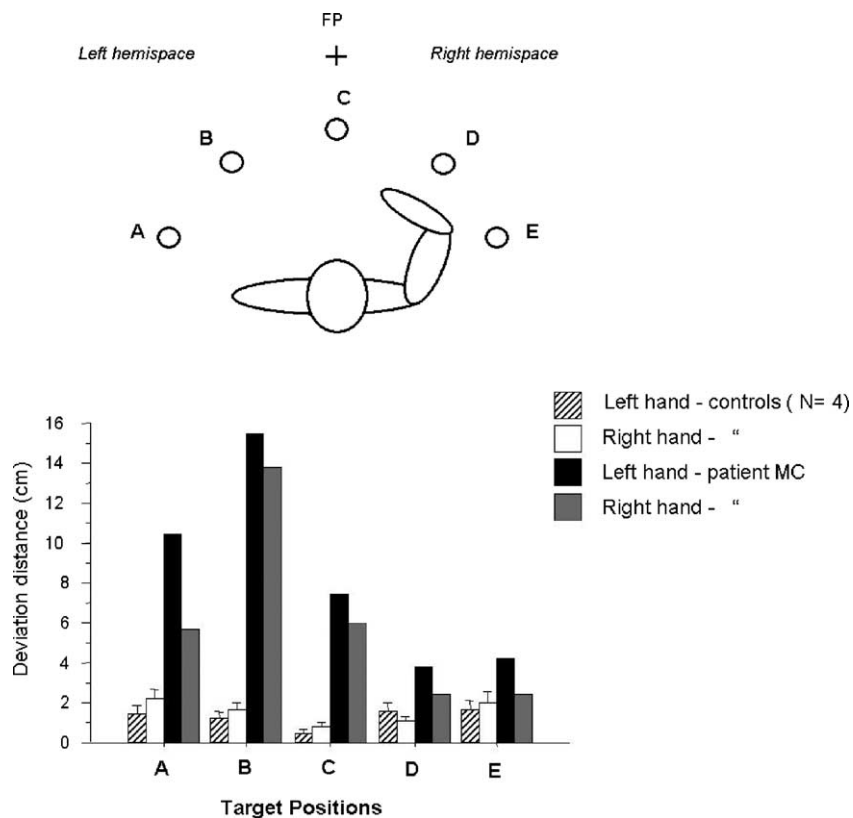


Fig. 2. Manual pointing task. Throughout the whole experiment, MC had to maintain fixation point (FP). Her pointing performance was much worse than age-matched healthy controls ( $N = 4$ ) for all locations, but especially impaired in left space.

$P < 0.093$ ) but not for MC ( $P = 0.18$ ). These visual search data demonstrate a bilateral disturbance in spatial attention in MC, again with a left-sided predominance. Moreover, this disturbance was found even for single-feature targets, and non-significantly worsened by the presence of distracters.

### 2.1.3. Illusory conjunctions

Visual binding of features (Friedman-Hill et al., 1995; Robertson et al., 1997) was tested by a simple identification task, where two coloured letters (one X and one O, one blue and the other red) were simultaneously presented to the left and to the right of a central fixation point for 1000 ms. Each letter of each colour could appear in the left or right visual field, yielding four possible combinations that were repeated 15 times (total number of trials: 60). The patient was explicitly told that there would always be two visual stimuli on the screen and was instructed to verbally report the letter identity and the colour of each stimulus. Responses were coded as follows: reports of right visual stimulus only was considered as left visual extinction, reports of left visual stimuli only were considered as right visual extinction, whereas misattributions of the left-sided colour to the right-sided letter (and vice and versa) were considered as illusory conjunctions.

**2.1.3.1. Results.** In this task, MC gave only two correct responses out of the 60. In the remaining 58 trials, MC gave

unilateral responses (e.g., she reported only one stimulus), among which 35 (58%) were left-sided extinctions, 9 (15%) were right-sided extinctions, and 12 (20%) were illusory conjunctions (e.g., the combination of a left-sided red O and a right-sided blue X was reported as a blue O or a red X). MC was thus severely impaired at detecting two visual events that were simultaneously presented, a deficit corresponding to “simultanagnosia” commonly observed in Balint syndrome. Again, her deficit was more pronounced in the left visual field. Importantly, she also showed clear evidence of illusory conjunctions consistent with a severe impairment in the representation of spatial locations (Friedman-Hill et al., 1995; Robertson et al., 1997).

### 2.1.4. Short-term visual-spatial matching

**2.1.4.1. Method.** The ability to form a stable representation of visual-spatial locations across short delays was tested using a two-step paradigm adapted from Humphreys (Humphreys, 1998). Each trial consisted of a sequence of two displays, each requiring a different task. The first display required a simple visual search for a coloured target as above (a green or red dot), presented either alone (no distracter condition) or among black dots (fixed set size,  $n = 16$ ; all dots' size  $\sim 0.75^\circ$ ). Target and distracter locations were randomly distributed across the screen, and varied

from trial to trial (50% of targets on the left and 50% on the right side). The first task was to report the colour of the target (red or green), which remained on the screen until response. Immediately after the response, all stimuli were removed from the screen. Following a blank interval of 2 s, the second display was presented, in which all stimuli reappeared but with the coloured target dot shown either exactly at the same location as in the first display (50% of trials) or at a slightly different location ( $\pm 2^\circ$  of rightward or leftward shift, 50% of trials). All distracters were unchanged. The task on this second display required judging whether the coloured dot was at the same or different location as compared with the first display, without any time constraints. Accuracy in location matching was determined for each visual field. MC's performance was compared to that of five age-matched controls.

**2.1.4.2. Results.** MC showed very poor accuracy in location matching performance (mean 61% correct) compared to healthy subjects (mean 97% correct). Whereas she was at chance when the target was alone (50% correct), her performance significantly improved in the presence of distracters (72% correct, unpaired *t*-test,  $t(70) = 2.0$ ,  $P = 0.05$ ), consistent with a benefit for spatial coding of object relationships as previously reported (Humphreys, 1998). Healthy controls also showed a similar trend for benefiting from the presence of distracters (95% correct without, versus 98% correct with distracters; one-tailed *t*-test  $t(4) = 1.44$ ,  $P = 0.09$ ), which may be partly masked by performance being nearly perfect. In this task, MC showed no significant asymmetry between location matching in left and right visual fields (59 and 63% correct,  $P = 0.15$ ).

#### 2.1.5. Discussion of experiment series 1

The above experiments aimed at establishing visual-spatial performance across several tasks, requiring visual detection and discrimination, visual exploration, feature binding, short-term spatial memory, and visuo-manual reaching. Overall, a severe bilateral spatial disturbance was demonstrated across all tasks, including simultanagnosia, impaired visual search, illusory conjunctions, poor location matching, and marked optic ataxia. While these deficits clearly affected both hemispaces, there was a systematically greater impairment on the left side. A similar left spatial bias has often been described in Balint patients (Rizzo & Vecera, 2002). Moreover, this left predominance in our patient is consistent with her lesion being larger in the right than left hemisphere.

#### 2.2. Experiment 2: crossmodal spatial links in visuo-tactile interactions

This experiment provided our main test for the role of space in crossmodal interactions. Here, we specifically examined the effect of spatial congruency versus incon-

gruency between simultaneous visual and tactile events. The patient had to judge tactile stimuli unpredictably delivered to the right or left hand, while task-irrelevant visual stimuli were presented close to the location of either the stimulated or non-stimulated hand. Numerous studies in healthy subjects have shown links between sensory modalities during such tasks based on the spatial congruency of the stimuli (Spence, 2002). In particular, the spatial congruency between simultaneous bimodal events may allow their integration into a unified perceptual object, providing a basis for several powerful multisensory effects in perception, such as the ventriloquist's illusion (Bertelson, 1999; Stein & Meredith, 1993). Also, irrelevant visual events can elicit a strong and involuntary orienting of spatial attention during the concurrent discrimination of tactile events at the same location (Spence, 2002). These effects have been interpreted as evidence for supramodal spatial processes contributing to exogenous shifts of attention, which are presumably mediated by posterior parietal cortical regions (Macaluso & Driver, 2001). We therefore predicted that impaired representation of space due to bilateral parietal damage in our patient should disrupt such crossmodal links between touch and vision. Specifically, since the experiments above showed a severe impairment in visuo-spatial coding, particularly within the left hemispace, the goal of Experiment 2 was to determine if this impaired spatial processing also affected multisensory interactions between stimuli in different modalities. However, it could also be possible that multisensory interactions resulting in attentional capture effects may occur in areas outside parietal cortex (see Phan et al., 2000). If this was the case, then such processes might still produce some crossmodal effects in our patient despite her parietal lesion and her severe spatial disorder.

#### 2.2.1. Method

The patient sat in front of a computer screen (40 cm width  $\times$  30 cm height) at a distance of approximately 30 cm, with each hand positioned just below the lower edge of the screen, approximately 20 cm to the left or to the right of the screen's centre, so as to allow spatial proximity between tactile stimuli delivered to the hands and visual stimuli presented on the screen. The room was dimly lit, and her hands remained visible throughout the experiment. Tactile stimuli were presented on each trial, accompanied or not by a simultaneous visual event on the screen.

Tactile stimuli were delivered through Oticon-A (100  $\Omega$ ) bone-conduction vibrators, which were taped between the thumb and index finger of each hand (stimulation surface 1.6 cm  $\times$  2.4 cm). Stimulation was delivered through a Sound Blaster 5.1 audio card (Creative Technology Ltd.), controlled by E-prime software (Psychology Software Tools Inc.). Unimanual stimulation was randomly delivered to either the right or left hand, and consisted of either a single continuous 150 Hz sinusoidal pulse (500 ms duration) or a double discontinuous 150 Hz sinusoidal pulse (two

brief vibrations of 200 ms duration separated by a 100 ms gap).

Tactile stimuli occurred alone on a third of all trials, or with a simultaneous visual event on two-third of the trials. When present, visual stimuli appeared for 500 ms and were high-contrast white circles (5 cm) at the lower right or lower left corner of the computer monitor just above the patient's hands and were controlled by E-prime. Half of these visual events occurred on the same side as the tactile targets (spatially congruent), and half on the other side (spatially incongruent). All visual events were task-irrelevant and MC was instructed to ignore them. The different types of tactile events (right- or left-hand stimulation) and visual events (congruent, incongruent, or no visual circle) were fully counterbalanced across conditions and given in random order within blocks of 96 trials

Throughout the experiment, the patient maintained fixation on a cross at the centre of the screen, which signalled the onset of each trial. Fixation accuracy was monitored by one examiner. The patient was asked to discriminate the number of vibratory pulses (one or two), regardless of the stimulated side. Speeded discrimination responses were made via two foot-pedals, one beneath the right foot and the other beneath the left foot of the patient, thus avoiding any hand movement related to the responses. Depressing the left pedal indicated a "single" pulse, whereas depressing the right pedal indicated a "double" pulse. Two blocks were administered on each of three successive days, following a series of 36 practice trials on the first day (which were excluded from analysis). Trials terminated 3500 ms after stimulus onset, irrespective of responses. RTs were calculated using only correct tactile discrimination responses, and pooled across single and double pulses. Errors and misses (no response within 3500 ms after stimulus onset) were excluded from further analysis. Throughout the experiment, white noise was presented to both ears via headphones, in order to mask the slight buzzing sounds produced by the tactile stimulators.

Five age-matched healthy controls (four female, mean age 48.8 year-old) were also tested in the exact same experiment, each completing three blocks of 96 trials during a single session.

### 2.2.2. Results

Accuracy and mean RTs were calculated for each hand and each type of visual-tactile congruency, for both the patient and the controls.

Healthy controls made incorrect responses on 4% of trials, without any difference between the trial types. Their mean RTs on correct trials (Table 2) showed a reliable facilitation for judging tactile stimuli when these were accompanied by a concomitant visual event on the same side (329 ms), as compared with a concomitant visual event on the opposite side (348 ms) or no visual event (369 ms), in keeping with crossmodal effects normally observed in other similar tasks (see Spence, 2002; Maravita et al., 2003). This was confirmed by a  $2 \times 3$  repeated-measure ANOVA on RTs with the

Table 2  
Spatial congruency in visuo-tactile interactions: RT means in Experiment 2

	Spatial location of visual cue		
	Congruent	Incongruent	Neutral
Tactile discriminative judgments			
Patient MC			
Left hand mean RT (ms) (S.D.)	415 (238)	406 (233)	525 (385)
Right hand mean RT (ms) (S.D.)	299 (327)	508 (316)	355 (262)
Healthy controls			
mean RT (ms) (S.D.)	329 (115)	348 (120)	369 (126)

factors of hand stimulated (left versus right) and congruency of the visual stimulus (spatially congruent versus spatially incongruent versus neutral, i.e. no visual stimulus), showing a significant spatial congruency effect ( $F = 7.12$ ,  $P = 0.016$ ) but no effect of hand ( $F = 3.16$ ,  $P = 0.15$ ) and no interaction ( $F < 1$ ). Thus, RTs to tactile stimuli were reliably faster with a spatially congruent visual cue than with an incongruent cue ( $t(4) = 3.23$ ,  $P = 0.032$ ) or no cue ( $t(4) = 2.82$ ,  $P = 0.047$ ), whereas there was only a marginal non-spatial facilitation with an incongruent visual cue as compared with a neutral condition without cue ( $t(4) = 2.14$ ,  $P = 0.098$ ). Importantly, an analysis of individual data indicated that each control subject exhibited a significant facilitation by congruent versus incongruent visual cues (all  $F > 3.38$ ,  $P < 0.05$ )

Patient MC made incorrect responses on 24% of trials across all blocks, including either discrimination errors (19% of trials) or misses (5% of trials), but these errors showed no consistent pattern across the different stimulus conditions. Her mean RTs on correct trials were calculated for each hand and each combination of visual-tactile events, as in healthy subjects above. The results are shown in Table 2. These data revealed a selective loss of spatial cueing effects for the left hand in the patient MC. Her RTs were analysed by a  $2 \times 3$  ANOVA, using the factors of hand stimulated (left versus right) and congruency of the visual stimulus (spatially congruent versus spatially incongruent versus neutral, i.e. no visual stimulus). MC tended to respond slower to left-hand stimulation than to right-hand stimulation (450 ms versus 374 ms, respectively), although the main effect of hand was not significant ( $F = 2.23$ ,  $P = 0.13$ ). More importantly, unlike in healthy controls, there was no significant main effect of visuo-tactile spatial congruency ( $F = 2.24$ ,  $P = 0.11$ ), despite her tactile responses being slightly faster on congruent (367 ms) than on incongruent (441 ms) and neutral trials (443 ms). Critically, however, there was a significant interaction between hand side and visual-tactile congruency ( $F = 3.85$ ,  $P = 0.023$ ). This reflected the fact that RTs to tactile stimuli on the right hand were faster in the congruent condition than in the incongruent and neutral conditions, whereas judgments of tactile stimuli on the left hand were not significantly affected by whether visual stimuli were spatially

congruent or incongruent (see Table 2). This difference was confirmed by follow-up tests on the RT means for each hand. The effect of spatial congruency was highly significant for the right hand ( $F = 4.58$ ,  $P = 0.014$ ) but not the left ( $P = 0.16$ ).

Nonetheless, the discrimination of tactile stimuli on the left hand yielded a trend for faster responses when accompanied by either spatially congruent or incongruent visual stimuli, as compared with the neutral condition without any visual events (mean RTs 525 ms versus 410 ms, for neutral versus congruent + incongruent conditions pooled together;  $F = 3.70$ ,  $P = 0.057$ ). This suggests that the non-spatial facilitation effect was preserved in MC, e.g., due to some general alerting effects whereby the visual stimulus appearance on either side could speed tactile judgments of the left hand. By contrast, in comparison with the neutral condition, right-hand tactile judgments showed both a facilitation by spatially congruent visual events and an interference by spatially incongruent visual events (Table 2). These effects clearly demonstrate that the lack of spatial integration between vision and touch on the left side was not due to an impairment in detecting left visual stimuli, since left visual events did influence tactile performance for both the left hand (though not in a spatially selective way) and the right hand (in a negative way).

### 2.2.3. Discussion of Experiment 2

These results show that tactile discrimination with the left and right hand was differentially influenced by simultaneous visual events occurring at the same or at another spatial location. Even though visual cues were spatially uninformative about the location and type of tactile targets, congruent spatial mapping between visual and tactile events produced a significant effect on the right hand, such that our patient's tactile performance was facilitated by a concomitant visual stimulus on the same side and slowed by a concomitant stimulus in the opposite hemisphere. In contrast, no such spatially-specific effects were observed for the left hand, where visual stimuli in either location facilitated reaction times. Thus, irrelevant visual events influenced tactile performance during right hand touches, similar to crossmodal effects typically observed in healthy subjects (Macaluso, Frith, & Driver, 2000). But the same irrelevant visual cues did not affect performance in a spatially-selective manner during left hand touches. This pattern suggests that crossmodal spatial mechanisms could still operate in MC within her right space, such that concomitant tactile and visual stimuli occurring on the same side were still integrated together and/or still influenced exogenous shifts of attention to their location (Macaluso et al., 2000; Spence, 2002), whereas these spatially-selective crossmodal interactions were abolished for visual-tactile events presented in her left space. This relative deficit on the left side corroborates the performance of MC in other visuo-spatial tasks, including visual search, short-term visuo-spatial coding, or visual-manual pointing (see experiment se-

ries 1), and extends these observations to multisensory processing.

However, our results in MC also suggest that crossmodal effects depended on the side of the hand being stimulated more than on the side of the visual stimulus. Therefore, the nature of this left-sided spatial coding deficit in MC cannot clearly be determined on the basis of these data alone. Both egocentric (body-centred) spatial coordinates and somatotopic limb-centred coordinates might be altered, but were confounded in the current experimental setting because the left limb was located on the left side of body space. Although no elementary sensory deficits were demonstrated by neurological examination (and primary somatosensory cortex was spared, see Fig. 1), tactile discrimination in the left hand was markedly slowed even in the neutral condition (e.g., without simultaneous visual events)—comparatively to the same extent as tactile discriminations made by the right hand during incongruent visual cues on the left side (i.e. under condition of diverted attention). These data would be consistent either with a mild subclinical sensory loss in the left limb, or with a more specific impairment in orienting attention toward the left personal space, even in the absence of any visual cues. The role of spatiotopic coding for tactile targets delivered to the left and right limbs was therefore investigated in the next experiment, by crossing the patient's hand positions in space.

### 2.3. Experiment 3: effect of hand crossing on tactile discrimination

This experiment aimed at clarifying the spatial nature (somatotopic or spatiotopic) of the tactile deficits observed for the left limb in Experiment 2 (i.e., slower tactile discrimination without visual cues, and the loss of spatially-specific visuo-tactile crossmodal interactions). We used the same tactile task as in Experiment 2, but without visual cues, while the patient had now to assume either of two different limb positions: (a) with her hands in the normal anatomic position, i.e., left hand in left space and right hand in right space; (b) with her hands crossed, i.e., left hand in right space and right hand in left space. Thus, in the latter condition, spatiotopic and somatotopic limb-centred coordinates were dissociated. A purely somatotopic deficit in tactile processing would predict slower RTs to left-hand targets irrespective of hand position, whereas a spatiotopic hypothesis would predict a modulation of RTs by hand position (e.g., slower RTs to right-hand stimuli delivered in left space and/or faster RTs to left-hand stimuli delivered in right space).

#### 2.3.1. Methods

The same experimental set-up was used as above. Two types of tactile stimuli were delivered, either a "single" continuous or a "double" discontinuous vibratory pulse, each presented for a total duration of 500 ms. All stimuli were given unimanually. The patient was asked to make speeded discriminative judgments about the number (1 or 2) of felt

Table 3  
Spatial limb position during tactile judgments: RTs means in Experiment 3

	Anatomic posture		Crossed posture	
	Left hand	Right hand	Left hand	Right hand
Patient MC, RT (ms) (S.D.)	543 (359)	345 (200)	385 (156)	398 (216)

vibratory pulses. Two different sessions were administered with the hands in the anatomical position and in the crossed condition (96 trials per blocks). Both hands were comfortably placed on a board in front of the patient. Responses were made by a foot-press using the same mapping in each condition (i.e. left foot pedal for “single” tactile targets, and right foot pedal for “double” tactile targets). The side and type of tactile stimuli was fully randomized. Again, white noise was presented to both ears via headphones to mask the slight buzzes produced by the tactile stimulators. Throughout the experiment, the patient maintained fixation on a central cross in front of her, aligned with her body midline.

### 2.3.2. Results

Accuracy did not differ between conditions (<15% errors overall). Table 3 presents mean RTs for the correct tactile judgments, for each hand in each posture condition. A two-way ANOVA on the RTs was carried out with hand (left versus right) and posture (anatomic versus crossed) as factors. A significant main effect of hand was found, caused by faster overall RTs to right-hand than left-hand tactile stimulation (370 ms versus 464 ms, respectively,  $F = 3.961$ ,  $P = 0.049$ ), but there was no main effect of posture (434 ms versus 391 ms, for anatomic and crossed postures, respectively,  $F = 1.12$ ,  $P = 0.29$ ). While the interaction of hand X posture only approached significance ( $F = 2.869$ ,  $P = 0.09$ ), importantly the asymmetry between the left and right hand RTs entirely vanished in the crossed posture condition as compared with the anatomic posture (see Table 3).

This was confirmed by additional ANOVAs on the hand effect performed for each posture separately, showing slower left responses in the anatomic condition only ( $F = 4.85$ ,  $P = 0.03$ , see Table 3). In contrast, hand asymmetry was not significant in the crossed posture condition ( $F = 0.075$ ,  $P = 0.78$ ). However, we note that tactile responses of the right hand in left space (398 ms) were still faster than those of the left hand in left space (543 ms).

### 2.3.3. Discussion of Experiment 3

This experiment allowed us to dissociate somatotopic spatial coordinates from spatiotopic (trunk and head-defined) coordinates. Comparison of MC's tactile performance in the uncrossed versus crossed hands conditions clearly demonstrates that RTs to touches delivered to her left hand were improved when the hand was positioned in the right hemisphere, whereas RTs to tactile stimuli delivered to the right hand were non-significantly affected by postural changes.

Such postural influences on left hand tactile processing support the hypothesis of a left-sided impairment in space representation, i.e. a deficit affecting the spatial coding of left tactile inputs. However, there was still an overall hand effect across all positions, with only minimal slowing of the right hand responses when placed in left space, suggesting that there may additionally have been a subtle sensory loss or limb-centred deficits for the left hand.

## 3. General discussion

The main goal of our experiments was to test whether bilateral parietal damage associated with Balint syndrome may result in a disorder of space representation that disrupts crossmodal interactions between sensory events occurring at the same location. Standard neuropsychological tests in our patient showed clear signs of severe bilateral parietal dysfunction, including optic ataxia, simultanagnosia, difficulties in many visual-spatial perceptual tasks (dot counting, position discrimination, judgement of line orientation), together with left–right disorientation, finger agnosia and dyscalculia. In contrast, faces, shapes, and colours were correctly identified when presented alone. A more detailed assessment of visual-spatial capacities also showed bilateral deficits in visual search, severe visual extinction for simultaneously presented objects, illusory conjunctions of features, and poor performance in a location matching task within both hemifields. These different tasks presumably rely on several distinct neural substrates in the parietal lobes (especially optic ataxia, typically due to dorsal lesions within intraparietal sulcus; see Perenin & Vighetto, 1988; Milner et al., 1999), but altogether converged to demonstrate that MC suffered from a severe bilateral disturbance in spatial processing, generally more pronounced in the left than right hemisphere.

Based on recent studies suggesting a critical role of the parietal lobes in crossmodal spatial interactions in animals and humans (Maravita et al., 2003; Spence, 2002), we predicted that a severe spatial disturbance after bilateral parietal damage in MC should impair crossmodal interactions induced by spatially congruent visual cues on tactile discrimination. Such crossmodal influences might result from exogenous shifts of attention towards a common location in space when sensory events in different modalities are bound into a unique supramodal representation (Macaluso & Driver, 2001; Spence, 2002), or from multisensory integration processes that can arise preattentively and independently of spatial attention shifts (Vroomen, Bertelson & de Gelder, 2001; McDonald, Teder-Salejarvi & Ward, 2001). Moreover, neurophysiological data suggest that supramodal spatial representations may implicate not only parietal cortex, but also other brain regions in the ventral premotor cortex, putamen, or superior colliculus (Stein & Meredith, 1993; Graziano, 2001), and that multisensory integration, in general, may involve sensory cortical areas outside the parietal lobes (Macaluso & Driver, 2001; McDonald et al., 2001;

Calvert, 2001; Murray et al., 2004a,b; Schroeder & Foxe, 2002; Foxe et al., 2000; Amedi, Malach, Hendler, Peled, & Zohary, 2002). Hence, some crossmodal interactions might possibly still be functioning in Balint syndrome despite biparietal lesions (e.g., see Phan et al., 2000). However, our data provide new evidence that interactions between simultaneous tactile and visual events was severely compromised in our patient, especially in her left space, confirming a critical role of posterior parietal areas in crossmodal interactions based on a multimodal spatial representation.

In our patient, visual-tactile spatial interactions were examined during a tactile discrimination task while irrelevant visual cues were simultaneously presented on either the same or opposite side as the tactile stimulus, or were absent. Critically, we found that a visual cue presented simultaneously with stimulation of her left hand induced a facilitation of responses to tactile targets on the left hand, irrespective of whether the visual cue was next to or distant from her left hand. In contrast, a visual cue near the right hand improved responses to tactile stimuli delivered to that hand, whereas a visual stimulus near the opposite hand caused a significant interference. These data suggest a lack of spatially-selective crossmodal interactions in the left hemispace, which was not simply due to a deficit in perceiving the left visual cue (e.g., left visual neglect), since left visual events significantly modulated tactile performance on the right hand. Thus, crossmodal interactions were not entirely lost in the patient, but more specifically impaired on the left side. Although our study was not specifically designed to distinguish whether visual-tactile effects observed in this task were mediated by exogenous shifts of spatial attention or sensory interactions independent of spatial attention (e.g., see McDonald et al., 2001; Vroomen et al., 2001), we believe that such a loss in the co-registration of visuo-tactile events in left space might at least partly relate to a damaged supramodal representation of space (Spence, 2002; Maravita et al., 2003) that may also be implicated in the co-existing deficits of spatial attention in this patient (e.g., in visual search or feature binding; see Friedman-Hill et al., 1995; Robertson et al., 1997).

Our findings also suggest that MC's altered pattern of crossmodal interactions between visual and tactile stimuli on the left side (versus the pattern seen on the right side in her case and that seen on both sides in healthy controls; see Experiment 2) may not solely involve a strict sensory or somatotopic disorder of the left hand. Rather, as the results of Experiment 3 suggest, our patient's behaviour likely follows from an alteration in both limb-centred and body-centred coordinates. Specifically, Experiment 3 showed that her responses were slower to left- than right-hand touches when the left hand was placed in left space, but not when it was placed in right space, suggesting a deficit in egocentric spatial coding of left tactile stimuli, at least of similar magnitude to any primary sensory deficit in the left hand. In contrast, no such postural effects were observed for responses to right-hand stimulations. Moreover, in Experiment 2, responses to left-hand touches were disproportionately

slowed in the absence of a visual cue (to the same extent as right-hand touches delivered with an incongruent distracting visual event), whereas a concomitant visual cue on either side produced a spatially non-specific improvement in tactile RTs. Altogether, these data indicate that a deficit in orienting attention to tactile events on the left-hand was exacerbated by placing this hand in left space, whereas orienting to tactile events on the right hand was not significantly affected by spatial position. This pattern suggests that left hand deficit in MC was not determined by somatotopic coordinates alone (i.e., centred on the left limb), nor by spatiotopic coordinates alone (i.e., limb position in egocentric or allocentric space), but apparently reflected a combination of both limb-centred and trunk-centred representations. Single-cell recording data in the monkey suggest that such mixed representations might be subserved by neurons in parietal cortex (Andersen et al., 1997). Unfortunately, we could not investigate crossmodal interactions during crossed hand posture in our patient, due to her unavailability for further testing.

By contrast, we note that the facilitation of left tactile responses by a concurrent visual event on either side, as compared with the neutral condition without any visual stimulus, suggests that some crossmodal effect could still occur on the left side but in a non spatially-specific way. This effect may result from general alerting by the visual stimuli (Robertson, Mattingley, Rorden, & Driver, 1998) and/or summation of bimodal inputs (Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002; Murray, Foxe, Higgins, Javitt, & Schroeder, 2001; Foxe et al., 2000). In our task, healthy controls also showed a trend for faster responses with an incongruent visual cue as compared with no cue. These data therefore provide evidence for a dissociation between spatially-specific and spatially non-specific mechanisms of crossmodal integration, with only the former being disrupted by biparietal lesions in the patient.

The asymmetry of the visuo-tactile crossmodal deficit of MC is consistent with her worse performance on the left than on the right side in several other spatial tasks, and with her larger lesion in the right hemisphere. A predominance of left-side deficits has often been described in other Balint patients (Rizzo & Vecera, 2002). Such spatial asymmetries might reflect a general right-hemispheric dominance in spatial processes, and/or differences in the location or size of lesions in each hemisphere. Moreover, lesions in our patient were more posterior and inferior in the right than in the left hemisphere, extending into the angular gyrus and the temporo-parietal junction. Several studies in healthy subjects have demonstrated activation of these areas during endogenous and/or exogenous shifts of attention in space, both in unimodal (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000) and multimodal paradigms (Macaluso et al., 2000). Furthermore, right inferior parietal cortex seems directly implicated in the crossmodal integration of sensory events (Downar, Crawley, Mikulis, & Davis, 2000). Our results therefore provide support for the view that neural populations in the dorsal part of the temporo-parietal junction

may have an essential role in the elaboration of supramodal map of space, where distinct sensory features are bound into a coherent representation of objects in space.

In summary, our study provides new neuropsychological evidence in support of an important role of parietal spatial representations in crossmodal interactions between visual and tactile inputs. Our results in patient MC show that bilateral parietal damage, with predominant involvement of the right inferior parietal lobule, resulted in a loss of spatial congruency effects between simultaneous visual and tactile events, specifically affecting the left hand placed in left space, but not the right hand in right space. By contrast, non-spatial sensory summation effects were preserved and may have distinct neural substrates (Murray et al., 2001). While our data are consistent with a role of inferior parietal cortex in supramodal representation of space, further studies are needed to clarify the exact nature and coordinates of such a representation (i.e., limb-centred or space-centred), and whether other representations in ventral premotor cortex and subcortical brain regions implicate similar or distinct spatial frames of references in crossmodal interactions.

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