Avoidance of obstacles in the absence of visual awareness

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The spatial character of our reaching movements is extremely sensitive to potential obstacles in the workspace. We recently found that this sensitivity was retained by most patients with left visual neglect when reaching between two objects, despite the fact that they tended to ignore the leftward object when asked to bisect the space between them. This raises the possibility that obstacle avoidance does not require a conscious awareness of the obstacle avoided. We have now tested this hypothesis in a patient with visual extinction following right temporoparietal damage. Extinction is an attentional disorder in which patients fail to report stimuli on the side of space opposite a brain lesion under conditions of bilateral stimulation. Our patient avoided obstacles during reaching, to exactly the same degree, regardless of whether he was able to report their presence. This implicit processing of object location, which may depend on spared superior parietal-lobe pathways, demonstrates that conscious awareness is not necessary for normal obstacle avoidance.

Keywords: visual extinction; consciousness; visuomotor control; spatial localization

1. INTRODUCTION

When we reach for an object, we take account of its size, shape and orientation, and its location relative to our body, arm and hand. The neural systems underlying these abilities are embodied largely in the superior parts of the posterior parietal cortex: the so-called 'dorsal stream' (Jeannerod 1997; Caminiti *et al.* 1998; Culham & Kanwisher 2001; Connolly *et al.* 2003). Our reaches are also extremely sensitive to the presence of potential obstacles in the workspace; we guard against collisions by veering away from non-target objects (Tresilian 1998). At present, there is no evidence from primate physiology or human functional imaging as to whether obstacle avoidance is subserved by the same superior parietal networks as the target-directed aspects of reaching. However, some recent studies of brain-damaged patients suggest that it may be.

First, in a study of 12 patients with left visual neglect following right-hemisphere stroke, we found that all except two showed normal patterns of avoidance when reaching between two objects, but they neglected the left object when asked to make a deliberate bisection of the space between them (McIntosh *et al.* 2003). The brain damage sustained by neglect patients often includes inferior parts of the parietal lobe but generally spares more superior parietal areas (Perenin 1997), where damage causes problems in visually guided reaching and grasping: so-called 'optic ataxia' (Perenin & Vighetto 1988; Jeannerod *et al.* 1994). In a second study, we tested two patients with bilateral optic ataxia to see whether their visuomotor problems extended to obstacle avoidance. Neither patient paid any attention to nearby obstacles during reaching, but both took full account of the same objects when asked to bisect the space between them (Rice *et al.* 2003). Our studies thus show a double dissociation between visual neglect and optic ataxia, complementing earlier evidence from goal-directed reaching (e.g. Perenin 1997), and suggest that superior, but not inferior, parietal networks are necessary for normal obstacle avoidance.

The visuomotor systems in the superior parietal lobe seem to operate in a largely automatic fashion, without evoking (or depending upon) conscious awareness of the stimulus properties they process. Evidence for this comes from patients in whom the perceptual system has been damaged (visual form agnosia; Goodale *et al.* 1991; Milner *et al.* 1991) or deprived of cortical visual inputs (blindsight; Weiskrantz *et al.* 1974; Perenin & Rossetti 1996). Despite profound impairments of perception, visuomotor control can be remarkably preserved in these patients. These visuomotor abilities, therefore, do not require conscious perception of the visual information that they use. The hypothesis of the present study is that the same is true for the avoidance of obstacles. Our observation that patients with visual neglect can avoid obstacles on the neglected side is consistent with this hypothesis (McIntosh *et al.* 2003), but no assessment of visual awareness was made in that study.

In the present study, we examine the role of awareness in obstacle avoidance by testing a patient with left visual extinction. Extinction is a common symptom of unilateral brain damage in which patients can detect single stimuli on either side of space, but fail to report stimuli on the contralesional side when these are paired with ipsilesional

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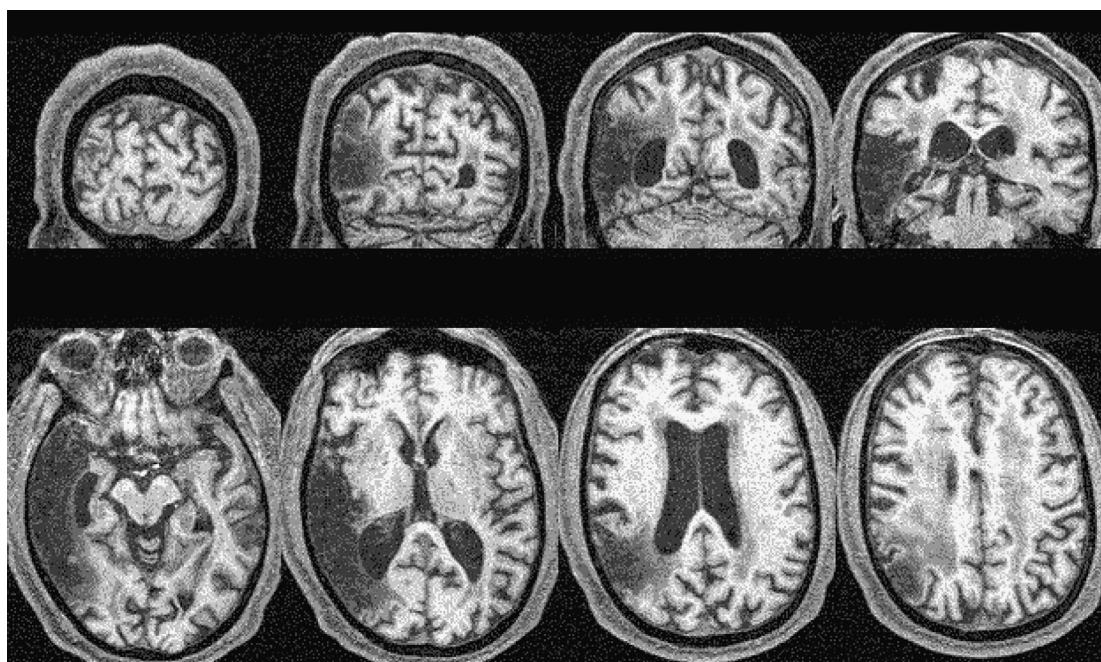DOI 10.1098/rspb.2003.2545
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Figure 1. MRI scan of patient V.E.'s brain, presented in coronal and axial sections, with the right hemisphere shown on the left. Extensive infarction is present within the distribution region of the right middle cerebral artery, with substantial involvement of the temporal lobe, though sparing medial temporal and hippocampal structures.

stimuli (Bender 1952; Driver *et al*. 1997). Extinction is conceptually close to neglect in that there is a unilateral deficit of awareness. However, while neglect is manifest in free vision, extinction is elicited only by brief bilateral stimulation. In recent years, several studies have shown that extinguished stimuli can be processed to a high level within the perceptual system (see Driver & Vuilleumier 2001). So far, this research has dealt exclusively with the processing of visual properties relevant to object identification, as indexed by 'offline' measures such as semantic priming. The present study is the first, to our knowledge, to test whether an extinguished stimulus can influence the performance of actions 'online'.

2. METHODS

Patient V.E. was a 75-year-old right-handed man who had sustained an ischaemic infarct in the territory of the right middle cerebral artery. V.E. had shown signs of visual neglect acutely but these had resolved by the time of testing (12 months after his stroke) according to standard tests. V.E. showed no motor impairments and no visual-field deficits to confrontation or to Tübingen perimetry. However, he showed reliable visual and tactile extinction to confrontation. Figure 1 shows a structural magnetic resonance imaging (MRI) scan of V.E.'s brain, taken following the present experiments; the results are consistent with an earlier computer-aided tomography scan. Much of the right temporal lobe is involved, with medial temporal and hippocampal structures being spared. The anteroinferior aspect of the right parietal lobe is also affected, amounting to *ca*. 25% of the right parietal volume. Despite slight damage to the anterior aspect of the right occipital lobe, the majority of the occipital lobe is spared. In addition, there is ischaemic change to the cerebral white matter bilaterally, especially on the right.

(a) *Experiment 1*

V.E. sat in front of a white horizontal board with a strip of grey tape (5 cm deep and 18 cm wide) forming a 'target zone' at the far end. Two thin dark poles (15 cm high) could be inserted into the board on either side of the midline, between the hand start position and the target zone. A small fixation flag was mounted centrally on a white backboard, at a height of 9 cm. The flag showed either a tick or a cross, discriminable only when fixated. The apparatus is depicted in figure 2*a*. The precise layout is illustrated in figure 2*b*; the zero lateral coordinate is aligned with V.E.'s mid-sagittal axis. V.E. wore liquid-crystal shutter glasses (*Plato*, Translucent Technologies Ltd) to control the period for which the stimuli were visible in each trial.

To ensure that V.E. fixated centrally at the beginning of each trial, he was told that his primary task was to identify the symbol on the flag. If this was a cross, he should say 'cross' and make no further response ('stop' trials). If it was a tick ('go' trials), he should reach out and touch the target zone as quickly as possible and then report any poles that he had seen (left, right, both or none). V.E. was permitted to touch any point within the target zone, so that the reach trajectory would be likely to optimize obstacle avoidance rather than end-point accuracy. Arm movements were recorded using an electromagnetic system (*Minibird*, Ascension Technology Ltd), which sampled the three-dimensional (3D) position of a magnetic marker, attached to the right index finger, at a frequency of 86.1 Hz. Data recording was time-locked to the opening of the shutter glasses at the start of the trial.

Trials were coded according to the fixation symbol (stop, go) and the poles present (left, right, bilateral). Go–bilateral trials were twice as frequent as go–left and go–right trials. Stop trials made up 23% of trials overall, with each pole configuration being equally likely. During preliminary practice trials, the open period of the shutter glasses was titrated to a duration at which V.E.'s verbal responses showed extinction on approximately half

of the go–bilateral trials (500 ms). V.E. cycled through a pseudo-random schedule of 78 trials at this exposure duration, until at least 20 go–bilateral trials had been collected in which he reported both poles, and at least 20 in which he reported only the right pole. In total, 123 trials were performed.

(b) Experiment 2

For experiment 2, the apparatus was modified to create a more symmetrical spatial layout (see figure 3). The poles were spring-loaded to fall rapidly through the table onto a soft pad below when the start button was released. This precluded the possibility of collisions and ensured that no tactile information could be gained about which poles were present. V.E. was not aware that the poles 'disappeared' in this way because he never released the start button within the brief exposure durations used. An infrared-based system (*Optotrak*, Northern Digital Inc.) sampled the 3D position of a marker attached to the right index finger at a frequency of 100 Hz. A voice-activated switch recorded the times of onset of V.E.'s verbal responses. Data recording was time-locked to the opening of the shutter glasses.

Experiment 2 comprised two tasks. First, V.E. performed a motor–verbal (MV) task under the same instructions as experiment 1: on go trials, he reached out to touch the target zone and then reported any poles that he had seen. Second, a verbal–motor (VM) task was performed in which the order of the responses was reversed: V.E. reported which poles he saw and then reached for the target zone. Preliminary testing failed to identify an exposure duration that reliably yielded approximately equal numbers of extinction and non-extinction verbal responses in bilateral trials. To ensure sufficient numbers of trials of each type, two exposure durations were used. The shorter duration (400 ms) biased V.E. towards extinction responses on bilateral trials (bilateral–report right), while the longer duration (600 ms) yielded a greater proportion of correct verbal reports (bilateral–report both). Each task was performed in four blocks of 48 trials, with a break after the second block. Exposure duration was blocked in an ABBA design beginning with the shorter. Within each block, there were 36 go trials: in 16 trials a single pole was present (eight left, eight right), in 16 trials poles were present bilaterally and in four trials no poles were present (to control for guessing in unilateral trials). The remaining 12 trials were stop trials (three each of left, right, bilateral and no pole conditions). Trial order within blocks was pseudo-random.

(c) Control experiment

Three healthy males (82, 72 and 72 years old) were tested on a reduced version of the MV task from experiment 2, to provide examples of normal obstacle-avoidance behaviour. Each performed 63 trials, comprising 48 go trials (16 each of left, right and bilateral pole configurations) and 15 stop trials (five each of left, right and bilateral pole configurations), in pseudo-random order. An exposure duration of 500 ms was used throughout.

3. RESULTS

(a) Experiment 1

V.E. gave only one inappropriate go response on a stop trial, indicating good control of fixation. The data from one go–left and one go–right trial were lost owing to movement-recording errors. Two go–left trials were excluded owing to erroneous reports of no poles present. V.E. never initiated his reaching movement less than 835 ms after the onset of the 500 ms viewing period (median

manual reaction time of 1091 ms), so all movements were executed without visual feedback.

Figure 2b shows the spatially averaged trajectories for each combination of pole location and verbal report. An ANOVA performed on the lateral displacement of the index finger as it crossed the virtual line joining the two pole locations was highly significant ($F_{3,85} = 140.79$, $p < 0.001$). Scheffé *post hoc* tests found reliable differences ($p < 0.001$) between all conditions except the two bilateral conditions ($p = 0.73$). The spatial path of V.E.'s hand was thus sensitive to the poles that were present, and his responses on bilateral trials were unaffected by whether or not he reported the left pole.

(b) Experiment 2

Across the MV and VM tasks, V.E. responded inappropriately on only one out of the 96 stop trials, indicating good control of fixation. Ten go trials (five MV, five VM) were aborted because V.E. failed to discriminate the symbol on the flag. One go–right and eight go–left trials were excluded from the MV data because no poles were reported. Six go trials were excluded from the VM data because the verbal response occurred after movement onset. No reaching response was initiated prior to the closure of the shutter glasses.

Figure 3 shows V.E.'s spatially averaged trajectories in the MV and VM tasks. In the MV task, the median manual reaction time was 930 ms and the verbal response was initiated after a median of 1975 ms. A one-way ANOVA performed on the reach trajectories, exactly as in experiment 1, was highly significant ($F_{3,109} = 68.14$, $p < 0.001$). Scheffé *post hoc* tests found reliable differences ($p < 0.001$) between all conditions except the two bilateral conditions ($p = 0.90$). In the VM task, the median verbal reaction time was 1080 ms and the reach was initiated after a median of 1410 ms. A one-way ANOVA on the reach trajectories was again highly significant ($F_{3,113} = 75.28$, $p < 0.001$). Scheffé *post hoc* tests found reliable differences ($p < 0.005$) between all conditions except the two bilateral conditions ($p = 0.89$).

The results in the MV and VM tasks replicate the findings of experiment 1, indicating that the outcome does not depend upon the temporal order of the verbal and reaching responses.

(c) Control experiment

The controls made very few inappropriate responses on stop trials (one, two and none for the three subjects, respectively). The verbal report of the poles present on go trials was always correct. Figure 4 shows the spatially averaged trajectories for each subject. Individual one-way ANOVAs, performed as before, were highly significant (control 1: $F_{2,45} = 103.11$, $p < 0.001$; control 2: $F_{2,45} = 55.36$, $p < 0.001$; control 3: $F_{2,45} = 68.86$, $p < 0.001$). All Scheffé *post hoc* comparisons showed reliable differences ($p < 0.005$).

Figure 4 indicates that the influence of the right pole on the reaching trajectory was always more pronounced than that of the left. This reflects the fact that, when responding with the right hand, objects on the right are more obstructive to the trailing arm. This asymmetrical pattern of avoidance was also seen in patient V.E. (figures 2 and 3). Additionally, although two of the controls
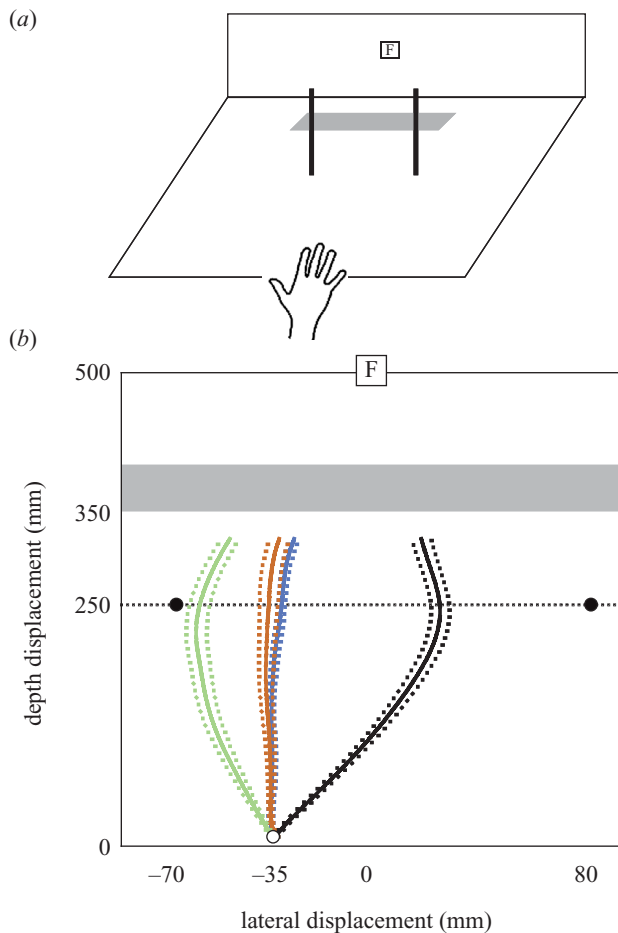
(a)

(b)

Figure 2. (*a*) The experimental set-up (see § 2*a*). (*b*) V.E.'s spatially averaged trajectories in each condition (dotted lines indicate standard errors). The zero lateral coordinate is aligned with V.E.'s mid-sagittal axis. F, fixation flag; grey shading, target zone; black circles, pole locations; white circle, start position. Black line, left–report left ($n = 18$); blue line, bilateral–report both ($n = 27$); orange line, bilateral–report right ($n = 20$); green line, right–report right ($n = 24$).

(a)

(b)

Figure 3. V.E.'s spatially averaged trajectories in: (*a*) the MV task (black line, left–report left ($n = 22$); blue line, bilateral–report both ($n = 31$); orange line, bilateral–report right ($n = 31$); green line, right–report right ($n = 29$)); and (*b*) the VM task (black line, left–report left ($n = 25$); blue line, bilateral–report both ($n = 20$); orange line, bilateral–report right ($n = 42$); green line, right–report right ($n = 30$)) (dotted lines indicate standard errors). The zero lateral coordinate is aligned with V.E.'s mid-sagittal axis. F, fixation flag; grey shading, target zone; black circles, pole locations; white circle, start position.

tended to reach to the right of centre, control 2's responses were biased leftwards like V.E.'s, suggesting that the patient's data were not abnormally shifted.

4. DISCUSSION

In a patient with visual extinction, we tested whether conscious awareness of an obstacle is necessary for that obstacle to influence a reaching response. Experiment 1 showed that the spatial paths of V.E.'s reaches were sensitive to any poles that were present, reflecting a strategic minimization of the risk of collision. Crucially, his performance in bilateral trials was independent of whether or not he reported the left pole. *Prima facie*, this seems to establish that the location of an extinguished object can be used to guide an action. However, an alternative interpretation might have been that the dissociation between motor response and verbal report did not depend on the different response modes *per se*, but on their temporal order. V.E. might have perceived the left pole explicitly at the time of initiating his reach, but somehow lost (i.e. extinguished) this awareness by the time of his verbal report. To exclude this possibility, we ran a second
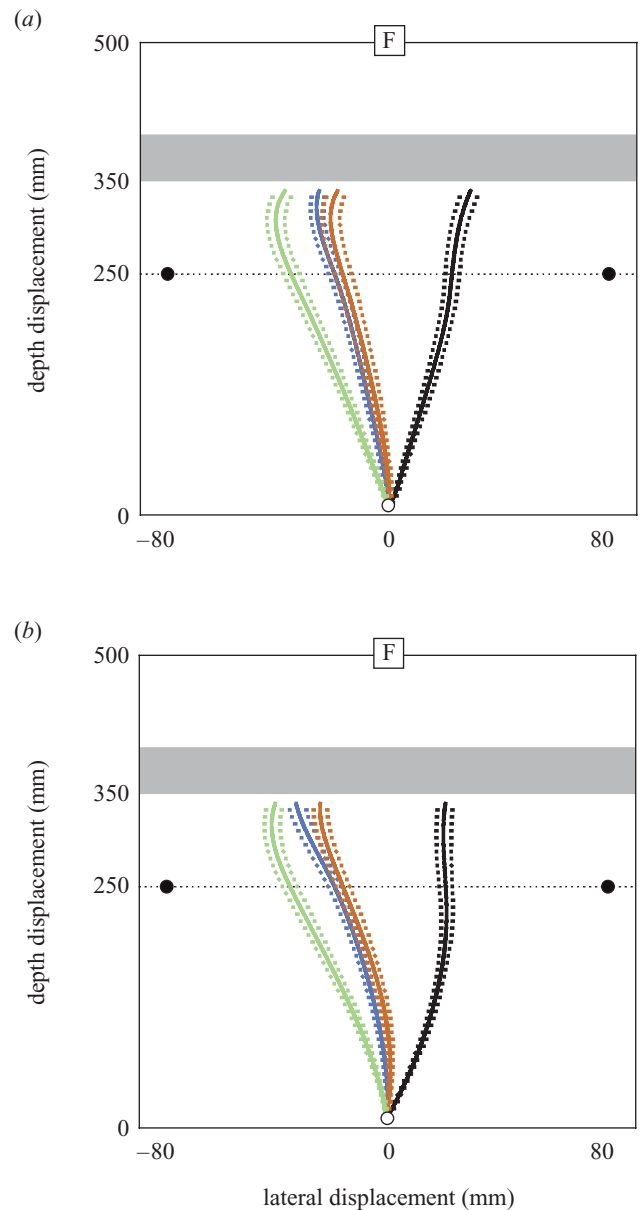
experiment in which V.E. performed the same basic task under two conditions, with the verbal report issued prior to or after the reach. The order of responses had no influence on the pattern of results. This robust demonstration of implicit processing of object location suggests that conscious awareness is not necessary for normal obstacle avoidance in reaching.

Of course, our conclusions apply to conscious awareness only as measured by the ability to report an experience verbally. Moreover, even the nature of the verbal report is known to influence extinction rates in some
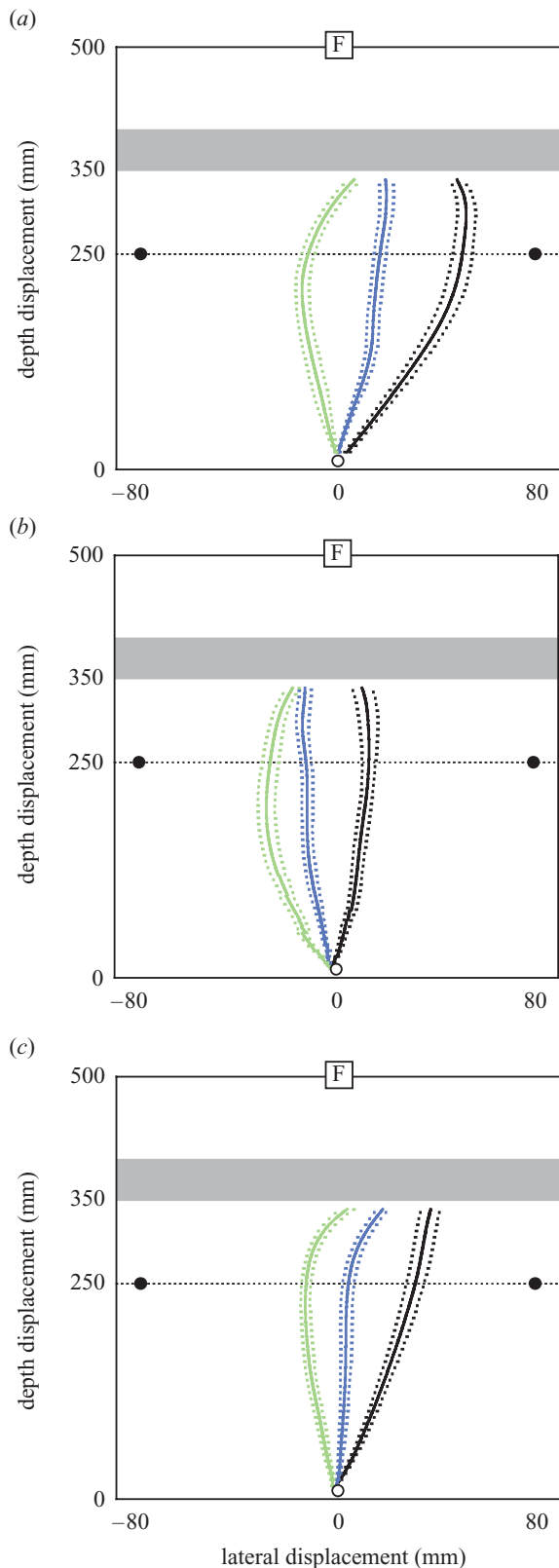
Figure 4. The spatially averaged trajectories of the three control subjects: (*a*) control 1; (*b*) control 2; and (*c*) control 3 (dotted lines indicate standard errors). The zero lateral coordinate is aligned with the subject's mid-sagittal axis. F, fixation flag; grey shading, target zone; black circles, pole locations; white circle, start position. Black line, left–report left ($n = 16$); blue line, bilateral–report both ($n = 16$); green line, right–report right ($n = 16$).

patients. For instance, extinction may be reduced if patients are asked to report the number of stimuli presented rather than to identify their locations (e.g. Vuilleumier & Rafal 1999). In the present study, we used a four-alternative forced-choice discrimination of the pole locations (left, right, both or none). This was chosen not only because it is the standard method of extinction assessment, but also to match the demands of obstacle avoidance, which requires stimulus localization rather than mere detection or enumeration. Even so, it might be objected that our method forced V.E. to be categorical about an awareness that may, in reality, have been graded. It could conceivably be argued that V.E. *was* aware of extinguished stimuli, but at a level that was insufficient for verbalization. Ultimately, this objection may be unanswerable; but if awareness were necessary for obstacle avoidance and V.E. had been only dimly aware of extinguished poles, we might have expected their influence to have been less than that of non-extinguished poles, and this was not observed.

The present findings converge with the results from other patient groups, summarized in § 1, to support the hypothesis that obstacle avoidance is guided by networks in the superior parietal lobe. The fact that V.E.'s avoidance of unseen obstacles was indistinguishable from his avoidance of those that he reported suggests that these networks normally operate unconsciously. Prior studies of extinction patients have demonstrated unconscious processing of perceptual properties such as colour, form and identity, as measured by offline testing. These implicit abilities appear to depend upon intact visual areas in the inferior temporal lobe (see review by Driver & Vuilleumier 2001). Although these ventral-stream areas may have been compromised in our patient, the superior parietal regions that we believe mediate obstacle avoidance were fully spared. Our data are thus consistent with the conclusion that implicit processing of extinguished visual stimuli can proceed within both ventral and dorsal streams, provided that they are intact in a given patient (see also Riddoch *et al.* 2003). However, our result does not imply that all extinction patients should show the same dissociation for all reaching tasks. An alternative outcome might be the impaired selection of target objects from non-targets on the *ipsilesional* side, in which case veering *towards* non-target objects could arise. This pattern was reported by Chieffi *et al.* (1993) in a patient with recovered neglect, though it is unclear whether their result depended upon the structure of the reaching task or the specific locus of the patient's lesion.

V.E.'s temporoparietal damage is common in patients with extinction (Vallar *et al.* 1994; Karnath *et al.* 2003) and is consistent with an important role for this region in determining the contents of perceptual awareness (Driver *et al.* 1997; Driver & Vuilleumier 2001). However, extinction can also follow superior parietal lesions (Vallar *et al.* 1994), which supports a role for certain dorsal-stream areas in selective visuospatial attention (Rizzolatti *et al.* 1994; Bisley & Goldberg 2003). Milner & Goodale (1995) suggested that 'visuomotor attention' and 'perceptual attention' might be partially separable entities, mediated by modulations of activity within dorsal- and ventral-stream networks, respectively, with the dorsal stream taking the lead in coordinating the two. They argued that

unilateral dorsal-stream damage might cause visual extinction by unbalancing the activity of attentional networks between the two hemispheres, which would transmit a similar imbalance to the ventral perceptual system. The present findings would be consistent with this directional influence, suggesting that a temporoparietal lesion can have a direct unbalancing effect on *perceptual* attention, without affecting *visuomotor* attention. However, if these speculations are correct, we can predict that the reverse pattern of extinction to that observed here should never occur. That is, it should not be possible to find a case of 'visuomotor extinction' in the absence of perceptual extinction.

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