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DOI
10.1016/j.neuropsychologia.2018.03.029
Publication date
2019
Document Version
Final published version
Published in
Neuropsychologia

Neuropsychologia 128 (2019) 270–275

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

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ARTICLE INFO

Keywords:
Action blindsight
Hemianopia
Residual vision
Pointing
Spatial localisation

ABSTRACT

Blindsight refers to the observation of residual visual abilities in the hemianopic field of patients without a functional V1. Given the within- and between-subject variability in the preserved abilities and the phenomenal experience of blindsight patients, the fine-grained description of the phenomenon is still debated. Here we tested a patient with established "perceptual" and "attentional" blindsight (c.f. Danckert and Rossetti, 2005). Using a pointing paradigm patient MS, who suffers from a complete left homonymous hemianopia, showed clear above chance manual localisation of 'unseen' targets. In addition, target presentations in his blind field led MS, on occasion, to spontaneous responses towards his sighted field. Structural and functional magnetic resonance imaging was conducted to evaluate the magnitude of V1 damage. Results revealed the presence of a calcarine sulcus in both hemispheres, yet his right V1 is reduced, structurally disconnected and shows no fMRI response to visual stimuli. Thus, visual stimulation of his blind field can lead to "action blindsight" and spontaneous antipointing, in absence of a functional right V1. With respect to the antipointing, we suggest that MS may have registered the stimulation and subsequently presumes it must have been in his intact half field.

1. Introduction

The paradoxical term *blindsight* refers to the ability of patients, who suffer from visual field defects due to damage to the primary visual cortex, to respond above chance level to visual stimuli in the blind areas of their visual field. The first scientific description of blindsight was published by Pöppel et al. (1973) who demonstrated that hemianopic patients made accurate saccades to light flashes presented in their blind half-field. Weiskrantz and co-workers (e.g. Sanders et al., 1974; Weiskrantz et al., 1974; Weiskrantz, 2009) took this initial observation one step further and showed that the effects could also be demonstrated using manual pointing and verbal forced-choice responses. Perenin and Jeannerod (1975) extended the evidence for residual manual localisation after cortical lesions, while the effect was not found for pattern discrimination in the impaired field of their patients.

Not surprisingly, this phenomenon attracted widespread attention, as it has major implications for theories of mental processing in general and consciousness in particular (e.g. Cowey, 2010), and blindsight is now one of the hallmarks of the cognitive neurosciences, not unlike the split-brain phenomenon (e.g. Gazzaniga, 2005). However, as is the case with split-brain research (e.g. Pinto et al., 2017), the fine-grained description of blindsight has remained controversial. Earlier criticism (e.g. Campion et al., 1983) focused on alternative explanations such as scattered light and/or rudimentary near-threshold vision. Although subsequent studies refuted most of these criticisms (see Cowey, 2010 for a review), there is still a need for a better description of the blindsight phenomenon in different, individual patients. Apart from blindsight for location, it has since been argued that blindsight patients may respond to flicker, contrast sensitivity, motion and wavelength (e.g. Weiskrantz, 2009; Stoerig and Cowey, 1992). In addition, above chance processing of higher-order properties has been proposed (e.g. Tamietto and Morrone, 2016). For instance, Trevethan et al. (2007) argued for preserved categorical perception and Solcà et al. (2015) for recognition of familiar faces presented in the blind field.

Over the years, it has become apparent that different patients may show differences in the nature of the phenomenon. In response to differences in the phenomenal experience of patients, two forms of it have been proposed by Weiskrantz et al. (1995). In type 1 blindsight, the patients experience no awareness of any kind, while patients with type 2 blindsight experience a non-visual experience that, and even where, something occurred. In addition, Danckert and Rossetti (2005) suggested three different types of blindsight. First, patients who are able to act upon stimuli in the blind field (e.g. by pointing or saccades) are classified as having "action-blindsight". Second, patients who respond

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https://doi.org/10.1016/j.neuropsychologia.2018.03.029
Received 8 September 2017; Received in revised form 14 March 2018; Accepted 22 March 2018
Available online 28 March 2018

on the basis of attentional processing of blind field stimuli are thought to have "attention-blindsight", and third, patients who demonstrate above-chance perceptual judgements for different stimulus characteristics presented in the blind field are classified as having "perceptual blindsight".

Thus, there are good reasons for in-depth, experimentally sound, studies of individual patients who demonstrate a form of preserved processing in their blind field, in order to formulate a reliable taxonomy of different forms of the blindsight phenomenon. In this paper, we sought to explore further the characteristics of the preserved processing in the patient MS, who has been studied in detail by Cowey and co-workers. MS suffers from a complete left homonymous hemianopia but can respond to visual stimulation in his blind field, notably to motion (e.g. Alexander and Cowey, 2010; Pavan et al., 2011). Alexander and Cowey (2009) used Transcranial Magnetic Stimulation (TMS) over the middle temporal visual area (MT* or V5) in the right hemisphere to show that the detection of motion in the blind field was dependent on cortical processing. The aim of the current study is to investigate the possibility of "action blindsight" in a case of well established "perceptual and attentional blindsight", employing a pointing paradigm. Also, we perform structural and functional magnetic resonance imaging (MRI) to evaluate the magnitude of V1 damage and the possibility of rudimentary V1 activation in both hemispheres, since the absence of a functional V1 is central to the definition of blindsight.

2. Materials and methods

2.1. Case history

MS is a former police cadet who contracted a febrile illness in 1970, at the age of 23. A full case description has been given by Newcombe and Ratcliffe (1975) and Ratcliff and Newcombe (1982), so we will only summarize the essential details here. The presumptive diagnosis was herpes encephalitis, but this was never confirmed by viral antibody studies. Radiology showed that most of the ventral temporal cortex of both hemispheres was destroyed extending to occipital cortex on the right, leaving him with a complete left homonymous hemianopia. However, his visual acuity in the seeing field is normal (6/6; N5 for near vision). He suffers from achromatopsia and his colour perception impairment has been studied extensively (Mollon et al., 1980; Heywood et al., 1991, 1994, 1996). He also has a severe object agnosia (successfully identifying only 8/36-line drawings) and prosopagnosia (e.g. Newcombe et al., 1989) but remains able to read accurately. His comprehension of what he reads is, however, affected by an impairment of semantic memory which can also be seen in the fact that he could only successfully name 20/36 objects from verbal descriptions of their functions. This semantic memory impairment is more marked for living than for non-living things (Young et al., 1989). More recently, Cowey and co-workers have provided convincing evidence for perceptual blindsight (e.g. Alexander and Cowey, 2009; Cowey, 2010; Pavan et al., 2011).

2.2. Experimental set-up

This experiment was set up to evaluate immediate pointing and reach-to-grasp movements to targets in the visual periphery. Target positions were arranged in an arc of 55 cm radius around MS's body. The centre of the arc was marked by a black cross and aligned with the subject's midsagittal axis. Throughout the trials, the subject was asked to fixate this cross. The first peripheral target position was approximately 5° from fixation with subsequent target positions at 5° intervals. The locations were indicated by black dots printed on a large plasticised white paper (841 mm x 297 mm) placed flat on the table. In addition, the fixation cross itself was used as a target location. A blue circle placed 5.5 cm from the table edge indicated the starting position for the index finger, in front of the central target location. The starting position

Fig. 1. Experimental set-up. The target position is depicted at 20° in the left visual field.

was 27 cm apart from the fixation cross. A schematic representation of the experimental set-up is shown in Fig. 1.

In a practice run performed the day before, MS was familiarised with the set-up. There were 23 practice trials performed with his right hand (9 left visual field, 9 right visual field, 5 central) and 24 practice trials with his left hand (3 left visual field, 13 right visual field, 8 central). During the practice trials, the target object was a light wooden cylinder (diameter: 9 mm, height: 161 mm), attached to a small square footing ($w \times h$: 34 mm × 5 mm). To enhance the target's discriminating features, it was replaced by a black cylinder during experimental trials.

Data were collected in two separate sessions. In the first session, the target object was the experimenter's finger, that moved up and down at one of the predefined target positions. In the second session, the target object was a black cylinder (diameter: 9 mm, height: 161 mm), attached to a wooden square board ($w \times h$: 34 mm × 5 mm). Performance was monitored through two video cameras placed in front and above the table.

2.3. Procedure

The procedure for both test sessions was identical. MS sat comfortably behind a table and rested his index finger on the starting position. Each trial started with MS fixating the central cross. After a variable delay, the investigator moved the target object in pseudo-random order to one of the locations along the arc. A verbal "go" signal, instructed MS to start a movement. In both sessions, performance in the sighted field was explored first to familiarise him with the task. MS was instructed to make fast pointing movements to the target whilst maintaining fixation on the central cross. For trials in the blind visual field, MS was encouraged to point to where he thought the target was located even when he could not perceive it. MS responded with his left dominant hand. Eye-fixation was monitored visually on all trials by a second investigator who sat opposite MS and confirmed using the front view camera footage.

2.4. Movement recording

Movements were recorded using a video camera mounted on the ceiling above the table, providing an overhead view. To be able to make measurements from the video images, perspective distortions were corrected using Final Cut Pro (version X) video editing software. Further video analysis was performed on a frame-by-frame basis in

Kinovea (version 0.8.15). First, the video was calibrated to real world units by setting the physical length of the white paper (29.7 cm). The origin of the coordinate system was set to the starting position for the index finger. Movement onset was defined as the frame in which the index finger first moved to leave the starting position. End of movement was defined as the frame in which velocity first fell back to approximately zero, and no significant changes in end position followed. The [*x*, *y*] coordinates of the marker at the tip of the index finger in the final frame of movement defined the end point of the reach. In a small number of trials, the index finger touched the investigator's hand before end of movement. In these files, the 2D coordinates of the place of contact defined the endpoint of the reach. End point errors were computed in the *x*- and *y*- direction by comparing the end point position of the index finger with the [*x*, *y*] coordinates of the target. For each trial, reaction time was calculated as the difference between target onset and movement onset.

2.5. Statistical analysis

The 2D coordinates of the end points were converted to degrees of visual eccentricity. For each trial, the directional error in degrees was computed. All results are based on permutation testing using Matlab (version 2014b). Performance was compared between sessions to test for the presence of a session effect. Next, we randomly assigned the observed end points to target locations 100,000 times. For each permutation, the mean absolute error was recorded. The observed mean absolute error was compared with the distribution of means arising from random permutations. The P-value indicates the likelihood that observed performance is obtained by chance. P-values < 0.05 were considered significant.

2.6. Imaging stimuli and procedure

To evaluate V1 activity in both hemispheres, we analysed BOLD activity from a different experiment (in prep). For this study, 96 visual stimuli (coloured photographs, see Kriegeskorte et al., 2008; Kiani et al., 2007) were used. To improve visibility, object size was increased with respect to the original study. During the task, stimuli were presented foveally while the participant performed a fixation task. One run of 96 stimuli lasted 6 min and 24 s. MS participated in 4 different runs.

2.7. Image acquisition and analysis

The subject was tested using a Philips Achieva 3 T MRI scanner with a 32-channel head coil. The subject participated in multiple recordings, relevant for this paper are the T1-weighted anatomical 3D acquisition (TE = 4.58 ms, flip angle = 8°, FOV = 240 × 256 × 200 mm, slice-thickness = 0.8 mm, voxel size = 0.8 × 0.8 × 0.8 mm, 250 slices acquired using Turbo Field Echo) and the functional GE-EPI (TR = 700 ms, TE = 27 ms, flip angle = 52°, MultiBand-factor = 6, FOV = 224 × 142.32 × 224 mm, slice thickness = 2.4 mm, slice gap = .24 mm, voxel size = 2.33 × 2.33 × 2.64 mm, 54 slices with ascending acquisition).

BOLD-MRI data were preprocessed and analysed using FSL 5.0.9 (Jenkinson et al., 2012) and MATLAB (2016). Functional data were corrected for motion. No slice-timing correction was performed. Next we filtered the data, both spatially (1.4 mm) and temporally (Savitzky-Golay, 200 s, 5th order polynomial). To decompose the BOLD signal from noise, we performed an ICA denoising procedure (FIX-ICA, Salimi-Khorshidi et al., 2014; approximately 20% of the variance in the data was removed). After preprocessing, time series were modelled using a double γ hemodynamic response function in a stimulus on vs. stimulus off GLM design using FSL FEAT. Motion and average brain-activity were used as nuisance regressors. The four runs were combined in a higher-level fixed effects analysis. We report voxels with a p value lower than < 0.01, uncorrected for multiple comparisons.

The experiments were approved by an ethics committee and written informed consent was obtained.

3. Results

3.1. Central pointing

MS completed a total of 10 trials to a target located at the fixation cross. Nine out of ten trials his directional error was less than 2°. The median reaction time was 355 msec. For the two trials with the largest error (1.8° and 2.9°), MS's reaction time was substantially higher (3.53 s and 4.10 s).

3.2. Blind field pointing

We explored the extent to which MS could point accurately to targets presented in his blind field. In total, there were 20 target presentations in his blind field across both experimental sessions. No trials were discarded because of eye movements. His median reaction time was 5.50 s. Visual inspection of the absolute directional errors revealed two outliers. In these files, MS demonstrated spontaneous, approximately mirror-symmetrical, responses towards the right (sighted) visual field. We observed this type of response before, during informal testing (practice trials), which is discussed further in paragraph 3.3. For the main analysis and figures, we excluded these two data points as we believe that they represent a different phenomenon.

There was no difference in performance between test sessions (*M* absolute error session 1: 5.0°, *M* session 2: 7.2°, $p = 0.52$). In order to increase power, data from both sessions were combined in further analyses. Overall, pointing performance in his blind field was significantly above chance level (average distance between pointed location and actual target location = 6.3°, $p = 0.001$). Fig. 2 shows the mean absolute directional error (degrees) for each target location. The data suggest his performance drops for target locations beyond 25°. Post-hoc exploratory analysis confirmed that pointing performance to targets in far periphery (30° and 35°) was not different from chance ($p = 0.80$).

3.3. Qualitative observations

We did not assess whether MS experienced any kind of awareness of the target in his hemianopic field. However, during the trials MS commented the targets “were completely out of focus” and “out of my range”. In two out of twenty presentations in his blind field, MS showed spontaneous pointing responses towards the right (sighted) visual field. Both observations were during session 1, when the target was the experimenter's moving finger. Interestingly, in practice runs, he often pointed to his right sighted field when targets were presented in his left field (in 9 out of 12 trials). The practice run was different from the test sessions in three ways: (1) MS was tested without the instruction to guess when he could not perceive the target; (2) the target was of a light wood colour instead of black; (3) the fixation point was behind the black cross that marked the centre of the arc. At the end of his pointing movement on trials where he showed this behaviour, MS often seemed uncertain about his performance, murmuring “No” or shaking his head. Unfortunately, these runs were not filmed from above and the 2D coordinates of the end points could not be extracted.

3.4. Imaging results

Anatomical scans revealed an, at least partially, intact primary visual cortex (V1) in both hemispheres. As shown in Fig. 3A/C, both the left- and right hemisphere show the presence of a calcarine sulcus. To indicate the transition from the left to the right hemisphere, Fig. 3B shows the meninges between both sides. The presence of a calcarine sulcus in both hemispheres indicates that patient MS has, at least

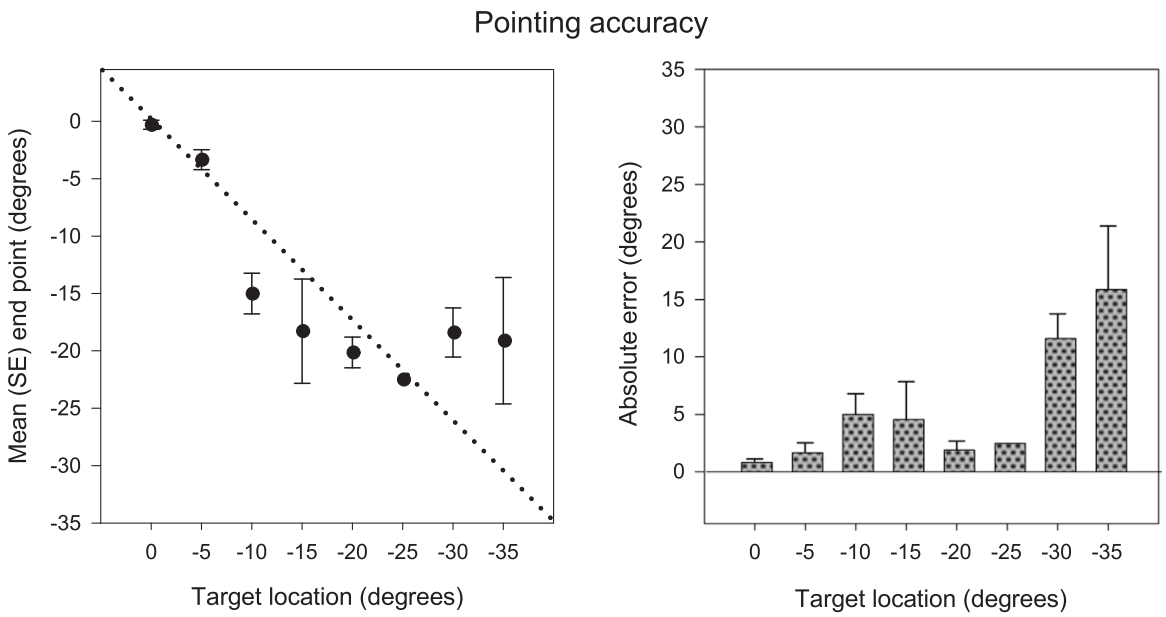

Fig. 2. Mean directional error in raw (left) and absolute (right) degrees for each target location. Error bars = standard error of the mean.

partially, spared V1 in both hemispheres. Further inspection of the anatomical scan suggests that this part of cortex in the right hemisphere, that could consists of parts of V1 to V4, is disconnected from subsequent cortical areas.

We evaluated the degree to which striate cortex responds to visual stimulation and concluded that, at a level of $p < 0.01$ (uncorrected) only the left hemisphere, presumably in or around V1, showed increased activation (Fig. 3E).

4. Discussion

Our findings demonstrate that MS was able to successfully point to targets presented in his cortically blind field. His performance was significantly above chance level in absence of acknowledged visual perception of the targets, which constitutes action blindsight. These results extend the previously documented blindsight phenomena in MS for motion detection and target localisation using a forced choice paradigm (Alexander and Cowey, 2009, 2010), and show the possibility of co-existence of the residual ability to localise an 'unseen' stimulus by both pointing and verbal responses. Neuroimaging revealed that

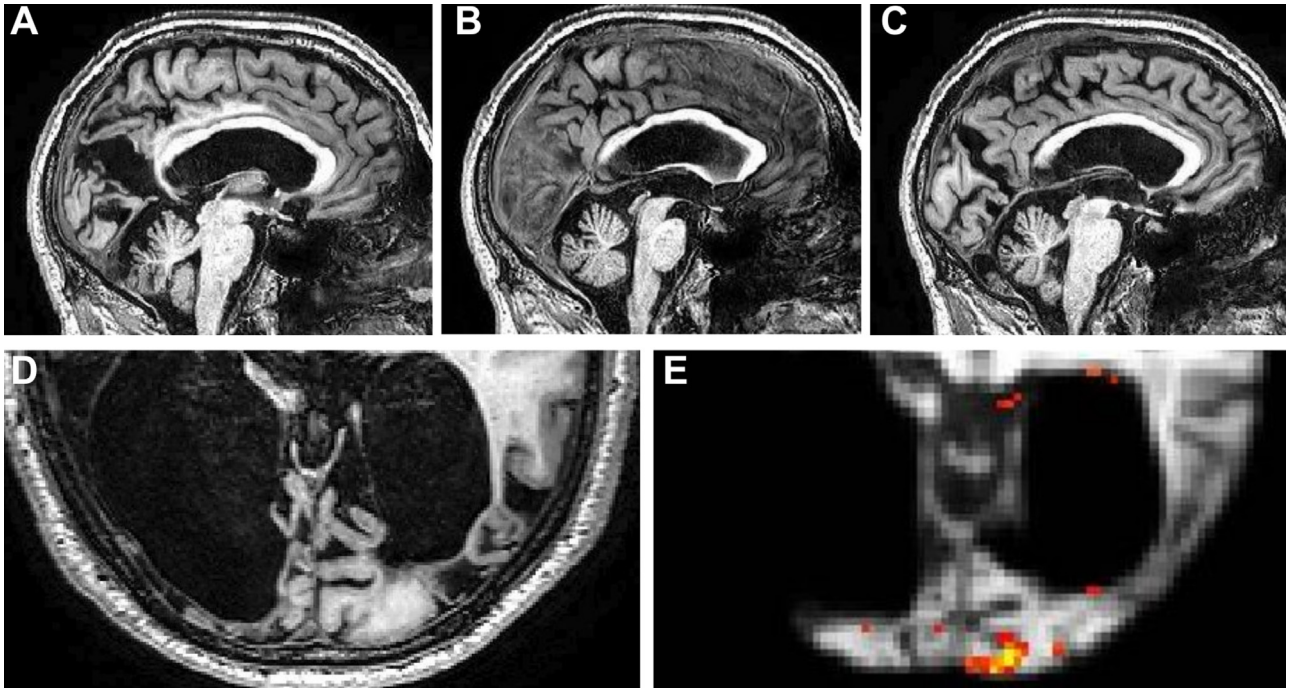

Fig. 3. Anatomical T1-weighted and BOLD-MRI images of patient MS. A) Sagittal view of the right hemisphere. **B)** Sagittal view of the meninges between both hemispheres **C)** Sagittal view of the left hemisphere **D)** Axial view of the occipital cortex. On these scans, the primary visual area (V1) can be seen on both sides. V1 in the right hemisphere doesn't connect to subsequent cortical areas. **E)** Striate cortex activation for patient MS in response to visual stimuli ($p < 0.01$, uncorrected for multiple comparisons).

although part of his right striate cortex is spared, it is structurally disconnected and not activated by visual stimuli.

There is considerable between- and within-subject variability of blindsight properties reported in the literature (e.g. Corbetta et al., 1990; Buetti et al., 2013). The required output (e.g. verbal, saccade, pointing) and specific stimulus features used to explore residual function differ between studies and can be critical for performance. Most prior studies have presented targets on a touch screen of a computer monitor or used small light-emitting diodes (LEDs). In this study, targets were real objects that were presented in normal lightning conditions. This suggests that the visual processes underlying above-chance localisation in blindsight include some degree of object-background segregation and are not solely depended on particular onset or illumination characteristics accompanying LEDs or on-screen targets. However, the movement of the target by the experimenter during the delay in between trials could have had an influence on MS's perception of target locations, though his reaction times do not suggest that he responded directly to the target displacement. Furthermore, we used manual pointing to investigate the possibility of “action blindsight” in MS. It has been suggested that localisation performance in blindsight cases may be depended on or is promoted by direct visuomotor interaction, as opposed to discrete manual responses such as finger tapping (Buetti et al., 2013). To what extent this is also true for MS and if he is able to perform equally well for other types of actions, such as obstacle avoidance or grasping remains open for further investigation.

Danckert and Rossetti (2005) proposed a taxonomy of residual behaviours demonstrated by blindsight patients, that separates motor responses to blind field targets from forced-choice guessing, and posits different neural pathways for these different types of blindsight. As mentioned, when TMS was applied to disrupt activity in area V5/MT$^+$ the motion blindsight in MS was abolished. Area V5/MT$^+$ provides input to the posterior parietal cortex (PPC) known to be important for visuomotor control (Born and Bradley, 2005). MS' spared visuomotor and perceptual abilities may thus be mediated through the same pathway via projections to and from MT$^+$. This suggestion does not necessary contradict the taxonomy proposed by Danckert and Rossetti (2005), who already pointed out that the difference between “action-blindsight” and “attention-blindsight” might reside in the terminal region of extrastriate cortex involved. Although the neural pathways that support blindsight are uncertain (for a review see Cowey, 2010), intact connections between the lateral geniculate nucleus (LGN) and extrastriate areas, especially area V5/MT$^+$, have been proposed to facilitate blindsight (Schmid et al., 2010; Ajina et al., 2015). As an alternative possibility, it has been suggested that cortical areas in the undamaged hemisphere have a role in action blindsight through compensatory interhemispheric connectivity (Celeghin et al., 2017). Lastly, it is interesting to look at the possible role of comorbidity, in this case whether the fact that MS also suffers from extensive damage to his ventromedial temporal cortex, resulting in achromatopsia and object agnosia, is related to the patterns of blindsight that he demonstrates. At this point in time, there are too few cases in the literature to make strong claims but it seems likely that visual function in the extrastriate areas (involving MT) is necessary. In contrast, it looks as if intact ventromedial temporal cortex in not a prerequisite for residual spatial abilities as demonstrated by MS.

When targets were located more peripherally than 25 degrees from eye fixation, eccentricity of the target was underestimated and end points no longer appeared related to target location. This effect of target eccentricity on spatial localisation accuracy in blindsight was also present in earlier findings of Perenin and Jeannerod (1975) and comparable to what has been observed in optic ataxia. The analysis of target eccentricity was post-hoc and the number of trials for each target position does not allow firm conclusions on the subject. However, it would be interesting for future studies to investigate this in more detail and to compare the effect of target eccentricity in blindsight to that described in optic ataxia. In line with earlier reports (Perenin and Jeannerod, 1975; Corbetta et al., 1990; Whitwell et al., 2011; Danckert et al., 2003; Ross et al., 2016), MS' pointing errors were larger than we would expect from normally-sighted control participants. In addition, the median time to initiate movement was substantially higher in his blind field than in central vision. This may be caused by uncertainty about events occurring within the affected part of his visual field. Overall, the results suggest input from a functional V1 is not necessary for localisation, though accuracy and speed do suffer from its absence.

Another interesting observation to discuss here is that on several occasions MS showed spontaneous antipointing behaviour. That is, when targets were presented in his blind field, he responded by pointing to his sighted field, though his pointing behaviour was not consistently mirror-symmetrical. This suggests to us that he has registered the visual stimulation but presumes it must have been in seeing half field (c.f. Weiskrantz et al., 1995 type 2 awareness). This type of response was much more common during the practice runs, when the target was a light wooden stick, and therefore, had less clear spatial boundaries. In addition, during practice MS was not prompted to give a response even when he could not perceive the target's location (as he was during the experimental trials). Alexander and Cowey (2010) investigated what stimulus features are processed in blindsight and show that performance was only successful when simple high-contrast stimuli were used. It may be that the target used during the practice runs was implicitly registered, but carried insufficient information about its location to allow an accurate response. We did not add catch trials, in which no target was actually presented in the current set-up. However, in a previous study of the effect of catch trials in a pointing paradigm, all hemianopics (three monkeys and one human (patient GY)) almost always directed their responses on blank trials towards the blind field (Cowey et al., 2008). Transpositions of stimuli to the opposite hemispace have been reported before in the context of allochiria (Meador et al., 1991). Both a shift of visual stimuli from the blind field to the intact field (Murakami et al., 2014; Walsh et al., 2012) and allochiria in manual pointing (Joanette and Brouchon, 1984; McCloskey and Palmer, 1996) have been descripted before but reports are scarce. As in blindsight, the pathways that mediate the phenomenon are unknown. Whether the antipointing behaviour exhibited by MS is indeed a variant of visual allochiria should be further investigated through specific testing.

Overall, the characteristics of preserved processing in patient MS observed so far suggest residual spatial abilities in his hemianopic field irrespective of response type (manual or perceptual). By studying different facets of the residual visual and visuomotor abilities in different patients, we can uncover a reliable taxonomy of blindsight. Subsequently, such a taxonomy can guide the search for neural pathways responsible for mediating blindsight.

Acknowledgements

Many thanks to MS for his participation in our experiments. This work was supported by an Advanced Investigator Grant by the European Research Council (ERC grant FAB4V (#339374) to EdH.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2018.03.029.

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