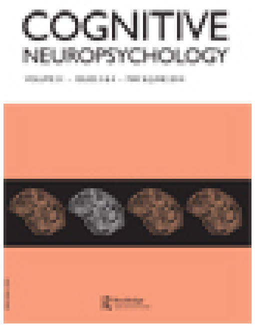

Cognitive Neuropsychology

ISSN: 0264-3294 (Print) 1464-0627 (Online) Journal homepage: http://www.tandfonline.com/loi/pcgn20

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To cite this article: Emily K. Prentiss, Colleen L. Schneider, Zoë R. Williams, Bogachan Sahin & Bradford Z. Mahon (2018): Spontaneous in-flight accommodation of hand orientation to unseen grasp targets: A case of action blindsight, Cognitive Neuropsychology, DOI: 10.1080/02643294.2018.1432584

To link to this article: https://doi.org/10.1080/02643294.2018.1432584

Published online: 15 Mar 2018.

COGNITIVE NEUROPSYCHOLOGY, 2018
https://doi.org/10.1080/02643294.2018.1432584

Routledge
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SHORT REPORT

Spontaneous in-flight accommodation of hand orientation to unseen grasp targets: A case of action blindsight

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ABSTRACT
The division of labour between the dorsal and ventral visual pathways is well established. The ventral stream supports object identification, while the dorsal stream supports online processing of visual information in the service of visually guided actions. Here, we report a case of an individual with a right inferior quadrantanopia who exhibited accurate spontaneous rotation of his wrist when grasping a target object in his blind visual field. His accurate wrist orientation was observed despite the fact that he exhibited no sensitivity to the orientation of the handle in a perceptual matching task. These findings indicate that non-geniculostriate visual pathways process basic volumetric information relevant to grasping, and reinforce the observation that phenomenal awareness is not necessary for an object's volumetric properties to influence visuomotor performance.

ARTICLE HISTORY
Received 14 October 2017
Revised 10 January 2018
Accepted 13 January 2018

KEYWORDS
Blindsight; dorsal stream; grasping; visuomotor; visual object recognition; parietal cortex; cortical blindness; PCA stroke

There are multiple parallel pathways within the early visual system, with different channels optimized for different visual information, including form, colour, and motion (Goodale & Milner, 1992; Jeannerod & Jacob, 2005; Livingstone & Hubel, 1988; Merigan & Maunsell, 1993; Sincich & Horton, 2005; Ungerleider & Mishkin, 1982). At the cortical level, areas within the ventral visual pathway support object identification and recognition in allocentric reference frames and represent material and surface properties that are also relevant for planning and executing functionally appropriate actions (Cant & Goodale, 2007; Gallivan et al., 2011; Goodale et al., 1994; Goodale, Westwood, & Milner, 2003; Schenk, 2006). The dorsal stream supports online transformation of visual information into action-relevant properties, including size, shape, location, depth, and orientation (Goodale & Milner, 1992; for discussion see Freud, Plaut, & Behrmann, 2016; Kravitz, Saleem, Baker, & Mishkin, 2011; Pisella et al., 2000; Schenk & McIntosh, 2010). A key question is the degree to which dorsal processing of stimuli can proceed independent of processing in primary visual cortex (V1), and independent of "awareness" or "perception". A direct means to test this is to study the visuomotor abilities of individuals with lesions that prevent processing of stimuli in V1, and thus who are blind across both eyes for a region of their visual field.

Blindsight refers to the phenomenon whereby individuals who are cortically blind due to a lesion to V1 or the optic radiations can still make accurate perceptual judgments and/or visuomotor actions to stimuli presented in the blind visual field (Cowey & Stoerig, 1995; Leopold, 2012; Pöppel, Held, & Frost, 1973; Stoerig & Cowey, 1997, 2007; Weiskrantz, 2009; Weiskrantz, Warrington, Sanders, & Marshall, 1974). "Action-blindsight", a term coined by Danckert and Rossetti (2005), refers to the ability of some individuals to make accurate saccades or visually guided reaches and pointing gestures to objects in the blind field, despite being phenomenally unaware of, and unable to explicitly describe those objects. Those residual visuomotor abilities are thought to be supported by one or both of two pathways that bypass V1: the superior colliculus to pulvinar to extrastriate cortex pathway, and the lateral geniculate nucleus to

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Supplemental data for this article can be accessed (http://doi.org/10.1080/02643294.2018.1432584).

extrastriate cortex pathway (Lyon, Nassi, & Callaway, 2010; Schmid et al., 2010; Schmid, Panagiotaropoulos, Augath, Logothetis, & Smirnakis, 2009; Sincich, Park, Wohlgemuth, & Horton, 2004; Takakuwa, Kato, Redgrave, & Isa, 2017).

There have been several case reports of cortically blind patients who retain an ability to make accurate reaches to objects presented in the blind field (Danckert et al., 2003; Marcel, 1998; Perenin & Jeannerod, 1975; Perenin & Rossetti, 1996; see also de Gelder et al., 2008). However, to our knowledge, there is only one reported case of a patient who could accurately rotate the wrist to grasp an unseen object, while being unable to make accurate explicit perceptual judgments about the object's orientation (Perenin & Rossetti, 1996). The patient reported by Perenin and Rossetti (1996), P.J.G., had a right hemianopia secondary to a lesion involving V1 and the optic radiations but sparing the occipital pole and not extending beyond the parieto-occipital sulcus. When asked to report the size or orientation of objects, P.J.G. performed at chance levels. However, when asked to post a card through slots at varying orientations, he was able to do so with remarkable accuracy (for precedent with this task from visual form agnosia, see Goodale, Milner, Jakobson, & Carey, 1991). P.J.G. was also able to scale his grip aperture appropriately and spontaneously when picking up objects presented in the blind field. The opposite pattern has been reported in individuals with optic ataxia, an impairment in object-directed reaching and/or grasping associated with lesions to posterior parietal cortex. Individuals with optic ataxia can make accurate perceptual judgments about objects, but have difficulty orienting, shaping, and/or locating their hands appropriately to grasp objects (Binkofski, Buccino, Dohle, Seitz, & Freund, 1999; Perenin & Vighetto, 1988; Pisella et al., 2000).

Careful study of individuals exhibiting dissociations between vision-for-action and vision-for-perception continues to hold tremendous potential in constraining theories about the functional organization of early and mid-level visual systems, as well as the subcortical and cortical inputs to the ventral and dorsal visual pathways. In the current report, we describe an individual with a lesion involving left lateral occipital and posterior parietal areas; he spontaneously and accurately rotated his wrist in flight to match the orientation of an object that was the target of his reach, despite having no visual awareness in that part of his visual field and being unable to report the orientation of the target in a perceptual matching task.

Case report

A.I. is a 75-year-old right-handed man who sustained an ischaemic stroke involving the left precentral gyrus and parietal and lateral occipital cortex, sparing the occipital pole (Figure 1); the lesion involved the parietal white matter, including the optic radiations, deafferenting early visual cortex (Figure 1). Following the stroke, A.I. had right-sided hemiparesis and a dense right inferior quadrantanopia (Figure 2a). At the time of the stroke, he reported having mild word-finding difficulty and impairments in mental imagery and short-term memory.

Testing timeline

We tested A.I. in two phases. In Phase I, A.I. was tested while an inpatient at Strong Memorial Hospital in Rochester, NY. This initial set of tests included a brief neuropsychological evaluation (3 days post stroke) and a neuro-ophthalmologic exam (8 days post stroke). The key experiments (grasping and perceptual judgments) that are the focus of the current report took place on Days 11–12 and 14–16 post stroke. After discharge, A.I. came into the lab for Phase II testing (22, 24, and 28 days post stroke), during which he completed a larger battery of neuropsychological tests, as well as a second neuro-ophthalmologic exam. It became clear that during the week between his discharge from the hospital and his Phase II testing in the lab, A.I. had enjoyed substantial visual recovery (Supplemental Figure 1); however, all data from the experiment in this report were collected while A.I.'s quadrantanopia was still present. In anticipation of a potentially rapidly changing clinical profile, the perceptual matching and grasping tasks described below were both always administered in each testing session.

Overview of neuropsychological tests

When first screened for the study (2 days post stroke), A.I. was oriented to self, time, and place. It was during this initial screening, when he was asked to reach out and grasp a pen held at different angles in his blind

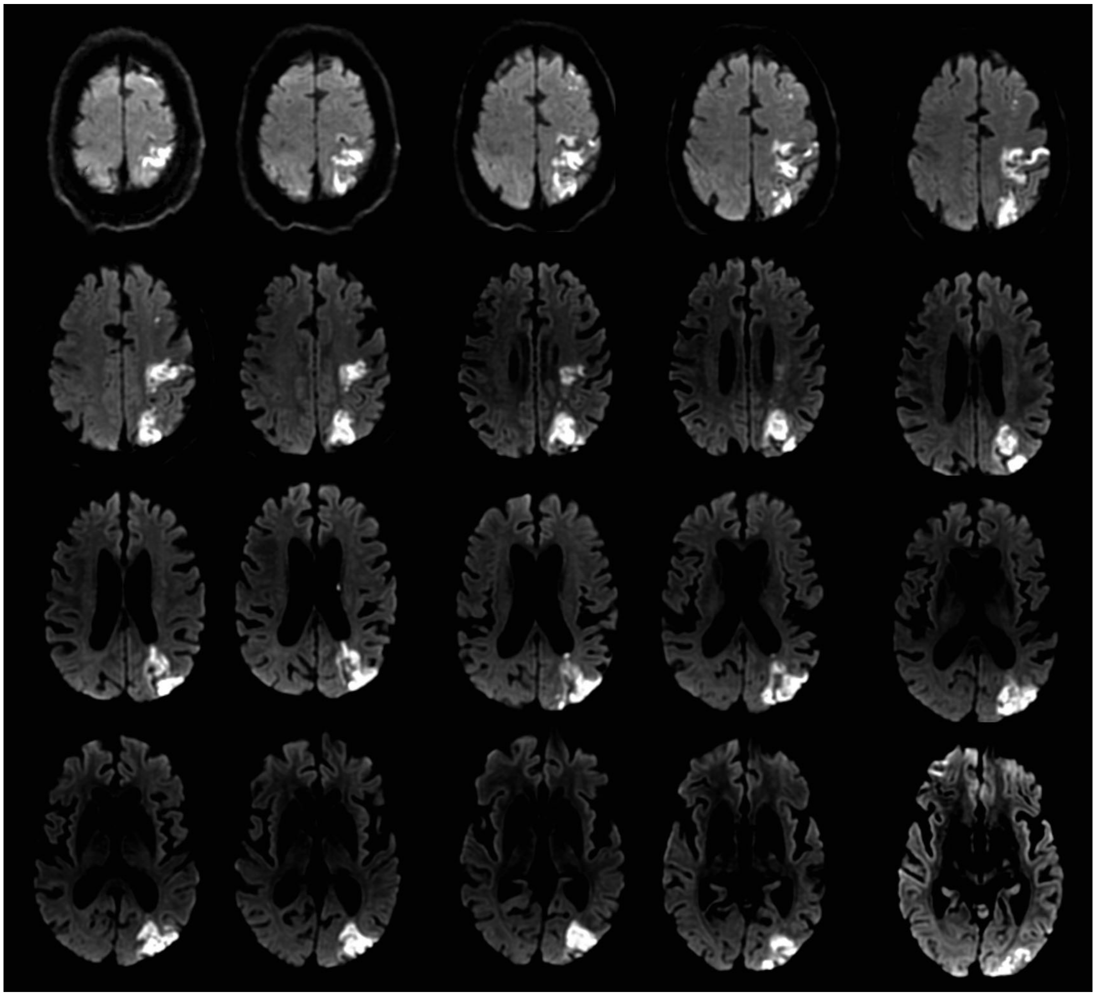

Figure 1. Magnetic resonance imaging (MRI) showing extent of acute stroke lesion. The images show diffusion-weighted MRI collected 1 day post stroke demonstrating a lesion in left parieto-occipital cortex involving Baum's loop but sparing the occipital pole.

visual field, that his ability to spontaneously rotate his wrist accurately was noticed. Below is a brief account of A.I.'s performance on neuropsychological tests at the time of the experimental investigation; see online Supplemental Materials for experimental designs and Phase II performance.

A.I. showed no signs of neglect on line bisection, or copying a drawing (Supplemental Figure 2A), performed well on a test of mid-level vision involving orientation matching administered at central fixation with free viewing (Riddoch & Humphreys, 1993), and was 87% correct for object reality decision (Riddoch & Humphreys, 1993), indicating no visual form agnosia. He demonstrated mild word-finding difficulty but no particular difficulties with object recognition. He was 85% correct for naming a subset of Snodgrass and Vanderwart pictures (Snodgrass & Vanderwart, 1980). In contrast, he demonstrated extreme difficulty constructing a mental image from memory and could not draw a giraffe from memory (Supplemental Figure 2b).

Visual field testing

A.I.'s vision was assessed with a full neuro-ophthalmologic exam (by author Z.R.W., at Flaum Eye Institute, University of Rochester Medical Center) including 24–2 Humphrey automated perimetry (each eye tested individually, with central fixation enforced). Humphrey perimetry demonstrated a dense right inferior quadrantanopia (Figure 2a); this was independently confirmed for the central 20° of vision using a letter detection and identification visual field task (online Supplemental Materials and Supplemental Figure 1). Note, however, that the perceptual matching and grasping task was performed more peripherally than the Humphrey perimetry test locations. For this reason, care was taken to ensure that both the

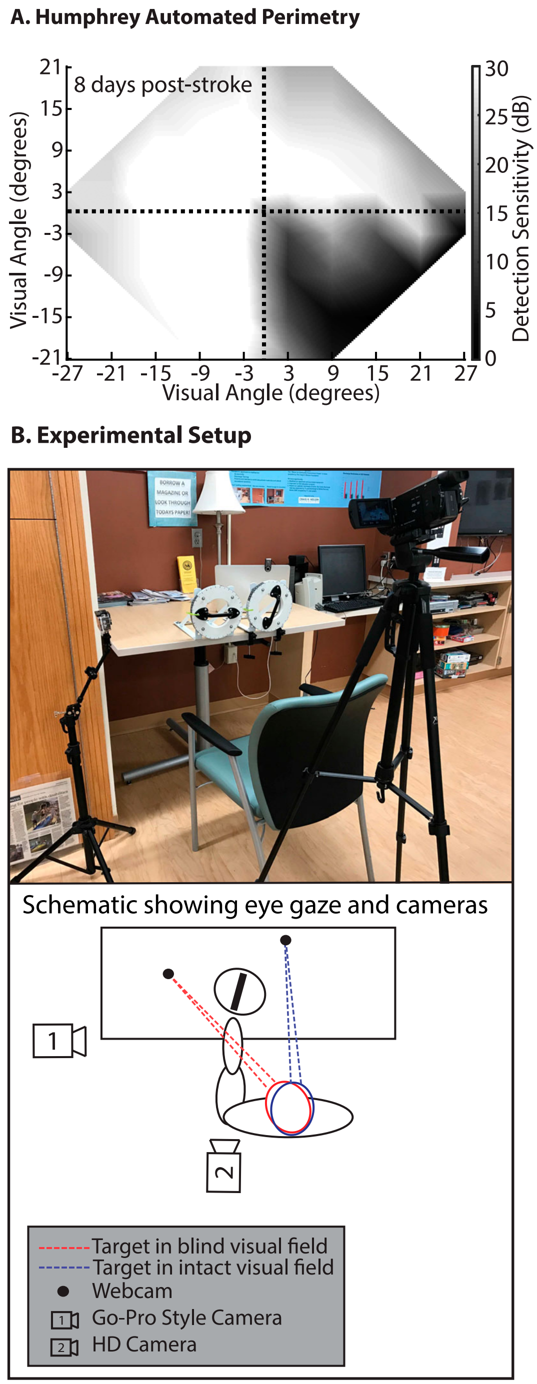

Figure 2. Visual fields and experimental set-up. (a) Automated 24–2 Humphrey visual field collected 8 days post stroke with both eyes combined into an interpolated winner map (as in Huxlin et al., 2009). Darkened areas show a right inferior quadrantanopia (see also Supplemental Figure 1). (b) Photograph and schematic of the experimental set-up during the visuomotor experiment.

perceptual matching task and the grasping task were administered during each session, which ensured that we consistently tested grasping in a visual field location where A.I. was not able to "phenomenally see" the stimulus.

Visuomotor study

Method

The visuomotor task described here was conducted while A.I. was an inpatient at the acute rehabilitation unit at Strong Memorial Hospital. He was first familiarized with the task over two days (Days 11 and 12 post stroke), then tested over three days (Days 14–16 post stroke).

A.I. completed two different tasks: a perceptual matching task and a reach-to-grasp task. Each task was completed in the intact visual field and the blind visual field in every testing session. The sequence of the tasks was counterbalanced across sessions. For example, on the first day of testing, the order was: reach-to-grasp in the blind field (Task "A"), matching in the blind field (Task "B"), reach-to-grasp in the intact field (Task "C"), and matching in the intact field (Task "D"), whereas on the second day, he completed the tasks in a "CDAB" order. For each trial, the handle was in one of six different orientations relative to the horizontal meridian: 0° (horizontal), 90° (vertical), and 30° or 60° to the right or left of the vertical meridian.

The study was designed as a 2 × 2 task (matching vs. grasping) by target location (blind or sighted). At the beginning of each testing block in the blind field, the experimenters verified the placement of the grasping device within A.I.'s blind field by asking him if he could see any part of the grasping device while fixating on a webcam. The webcam was moved so that the grasping device was located farther in his peripheral vision until he reported it completely disappeared from sight—that location was then tested in that session for both perceptual matching and grasping.

The two grasping devices were created so that they could be fastened to a table (Figure 2b). Each device had a handle fixed to a rotating annulus that was oriented in the fronto-parallel plane. Because of A.I.'s right-sided hemiparesis, all grasping and matching was performed with his left arm. Since testing took place outside the lab and across multiple days, care was taken to ensure that the grasping device was located at a similar eccentricity in the intact and blind visual fields each day. The centre of the target handle (for the matching and grasping task) was placed in A.I.'s blind field (22.5–31.5° right of fixation and 37.6–56.3° below fixation, ranges correspond to variation across testing sessions, Figure 2b). The handle itself subtended between 8° and 11° of visual angle (again, range depends on testing session).

Wrist orientation was recorded using an iPhone 4 and the "Advanced Gyroscope" application (Mercier, 2013). The application recorded real-time position information using the iPhone's native accelerometer. A.I. wore the iPhone in an armband on his left wrist. The application sampled wrist orientation in degrees relative to the horizontal plane at 10 Hz. The gyroscope was calibrated at the beginning and middle of each block so that it was set at 0° when A.I. grasped the handle in the horizontal orientation. Two video cameras also captured A.I.'s movements: a "go-pro"-like camera was positioned orthogonal to his direction of reach, and an HD-camera was positioned above and behind A.I. while a webcam recorded eye position for offline analysis (Figure 2b).

Matching task

The matching task was designed to assess A.I.'s perceptual abilities in his blind and intact visual fields. The second (manipulated) handle was placed in the intact field, just below fixation. For each trial, the experimenters temporarily occluded A.I.'s view of the model while setting the handle to one of the six pre-specified orientations (see above). Once set, the occluder was removed, and A.I. was instructed to manipulate the (visible) second handle to match the model (in his blind field) as closely as possible while maintaining fixation on the webcam. This task was repeated with the model in the intact field (lower left quadrant, 21–41° left of fixation and 33.5–58.3° below fixation, ranges correspond to variation across testing sessions) and the second handle in the intact field just below fixation. Over three sessions, he completed 84 trials with the model in the sighted field and 84 trials with the model in his blind field, yielding 14 trials for each of the six orientations.

Reach-to-grasp task

The reach-to-grasp task was designed to assess spared visuomotor ability in A.I.'s blind and intact visual fields. The grasping device was placed in either the blind field or the intact field as above. For each trial, the experimenters rotated the occluded handle an arbitrary number of times to prevent auditory cues from providing information based on a memory of its orientation from the last trial; the handle's orientation was then set at one of the six pre-specified orientations (see above). The occluder was then removed, and A.I. reached to grasp the handle as quickly and accurately as possible while maintaining fixation on the webcam. A specific starting position for reaching-to-grasp was not enforced, but A.I. generally rested his hand on the armrest or in his lap before each trial. A.I. completed 84 trials in the blind field and 84 trials in the sighted field, yielding 14 trials for each orientation in the impaired and intact visual fields. On a small number of trials in his blind field, A.I. would reach out without rotating his wrist, touch the handle with his knuckles, then orient his wrist and grasp the handle; these trials were excluded from the analysis ($n = 10$), and he was reminded to orient his wrist appropriately "in-flight". Throughout all testing, A.I. reported that he could not see the handle in his blind field and expressed surprise when he would reach out—in a way that he perceived to be random—and successfully grasp the handle.

Analysis

We conducted a frame-by-frame analysis of videos from the camcorder positioned behind A.I. and the camera orthogonal to his reaching trajectory (Figure 2b). For the matching task, we recorded the position of the model handle and the handle that A.I. manipulated. For the reaching task, we extracted his wrist angle from the iPhone at the time point corresponding to the last video frame before he made contact with the handle. While A.I. was completing the task, one experimenter monitored his gaze in real time so that testing trials in which he broke fixation were repeated, ensuring that all cells of the design had the same number of "clean" trials. We also inspected the webcam videos after testing, which ensured that A.I. maintained fixation throughout all trials. Results from the two handle orientations that mirrored each other (e.g., 30° and 60° to the right or left of the vertical meridian) were collapsed for analysis.

Results

As performance was consistent across all three testing sessions, and matching and grasping were performed within each session, all reported results reflect performance averaged across testing dates.

Matching

When both grasping devices were in A.I.'s intact visual field, he was able to orient the second handle to match the orientation of the model extremely accurately ($r = .99$, $p < .001$, Figure 3a), with an average magnitude of difference between target and actual orientation of 7.8° ($SD = 6.1$). However, when the model handle was placed in his blind visual field, he was unable to match the visible handle to the model ($r = .08$, $p > .50$, Figure 3b); the average magnitude of difference between target and actual orientation was 58° ($SD = 43.8$). When asked about his performance, he stated that he was guessing for all trials in which the model was presented in the blind visual field.

Reaching-to-grasp

When the grasping device was presented in his intact visual field, A.I. spontaneously oriented his wrist upon reaching for the handle with a high degree of accuracy ($r = .88$, $p < .001$, Figure 3c); his average deviation from the target orientation was 8.9° ($SD = 10.3$). In contrast to his poor performance in perceiving the orientation of the handle in his blind visual field, A.I. also spontaneously and accurately oriented his wrist when grasping the (unseen) handle ($r = .71$, $p < .001$, Figure 3d); his average deviation from the target location was 19.4° ($SD = 16.9$). When asked about his performance, A.I. asserted that he never had a percept of the handle in his blind field and was guessing the orientation of the handle every time. He never ceased to be surprised that he was accurate in grasping the handle (see Supplemental Video 1 for example trials).

General discussion

We have reported a dissociation between a complete lack of awareness of visual information and spontaneous rotation of the wrist during grasping in a patient with a lesion that deafferented early visual

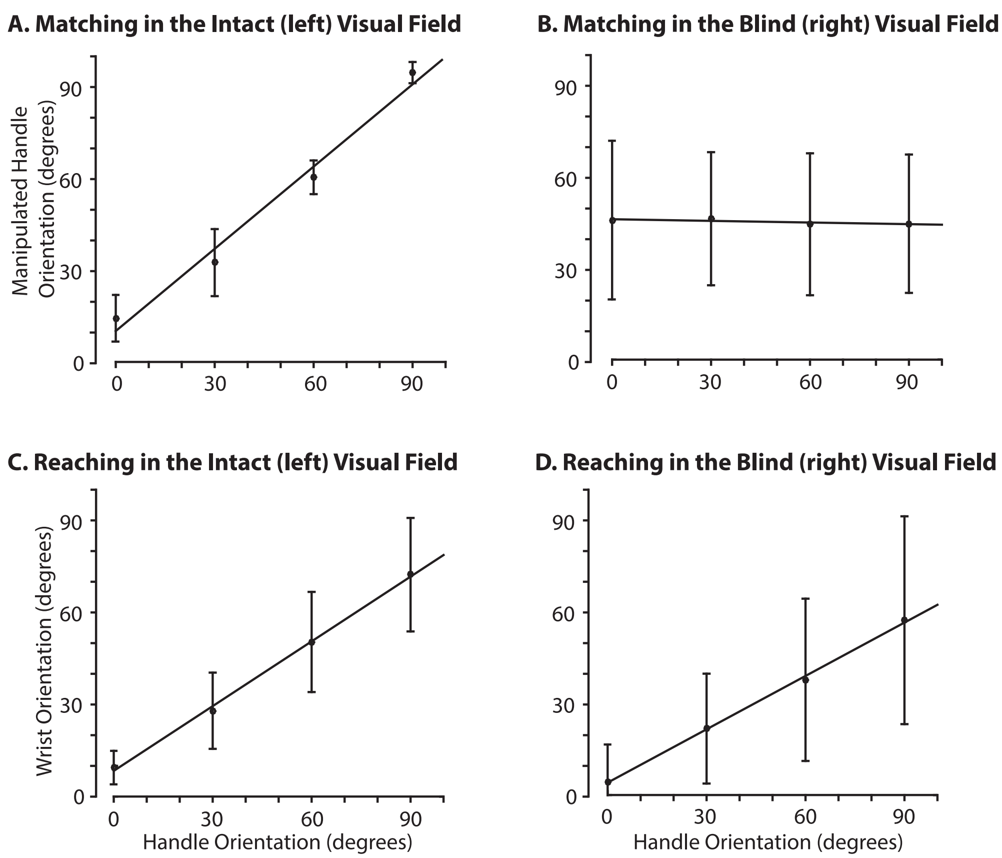

Figure 3. Dissociation between wrist orientation and perceptual matching. Results of perceptual matching and grasping experiment. Error bars indicate standard error of the mean. Manipulated handle angle compared to model handle angle when matching targets presented to the (a) intact (left) visual field and (b) blind (right) visual field; A.I.'s wrist orientation compared to target angle when reaching in the (c) intact (left) field and (d) blind (right) field.

cortex. A.I. was able to accurately perceive and grasp a handle that was presented in his intact visual field, but was unable to perceive a handle in his blind field; the key finding is that A.I. was able to accurately rotate his wrist to grasp the handle in his blind field. Clearly, his ability to accurately orient his hand during the grasping action means that visual information is being processed; this is despite the fact that he has no *experience* of vision. These findings are another demonstration of the dissociation between vision-for-action and vision-for-perception, first described in the context of visual form agnosia by Goodale et al. (1991).

To our knowledge, our findings represent the second reported case in the literature of a dissociation between accurate wrist orientation and impaired perception of objects presented in the cortically blind field, with the prior case described by Perenin and Rossetti (1996). One aspect of our case that is of particular interest is that A.I.'s lesion included posterior–lateral parietal cortex. His spontaneous and accurate accommodation of his hand's orientation to the orientation of the handle in the blind field might appear somewhat surprising given the extent of his putatively "dorsal" lesions. However, it is important to note that all grasping was performed by A.I. using his left (i.e., ipsilesional) hand, as it was not possible to test his contralesional hand due to his hemiparesis, which persisted throughout all of our testing sessions, even after he recovered a substantial amount of vision.

One account of A.I.'s intact ability to orient his hand to an unseen target in his blind field is that the damage in his left parietal lobule, in fact, spared the relevant regions of the dorsal pathway. In other words, while he had a parietal lesion, it may not have involved parietal regions that participate in dorsal visual analysis in the service of action. Another, more intriguing, possibility is that A.I.'s parietal lesion *would* have caused optic ataxia, except that it was not possible to test his ability to grasp targets with his contralesional hand. Because optic ataxia is classically a visuomotor impairment for grasping targets in the contralesional visual field with the contralesional hand, A.I.'s hemiparesis may have "masked" a possible optic ataxia. This issue can be addressed through studies of future patients with deafferenting or frank V1 lesions who do not have parietal involvement, or who have parietal involvement without motor impairments. The expectation would be that patients with cortical blindness and no parietal lesion would demonstrate accurate spontaneous wrist orientation while grasping with either hand. In contrast, patients with concomitant parietal lesions without hemiparesis may exhibit accurate wrist orientation when grasping targets in the blind field with their ipsilesional hand, but not with the contralesional hand (i.e., action blindsight *and* optic ataxia, within the same individual but dissociated across the two hands).

Conclusion

Critical insight about the type of information that is processed by non-geniculostriate pathways can be gleaned by studying patients with lesions that affect post-geniculate visual processing. The findings we have reported in this case study indicate that pathways that bypass V1 are sufficient to process the principal axis of elongation of an object that is the target of an action, and provide additional evidence for the dissociation between vision-for-action and vision-for-perception.

Acknowledgments

We are grateful to A.I. for his enthusiastic participation in these studies, to Duje Tadin for his assistance with the development of the letter detection and identification test and to the Seneca Nation of Indians, on whose traditional territory the University of Rochester resides.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was supported by the National Institutes of Health (NIH) [grant number R01NSO89069 to B.Z.M.]; a core grant to the Center for Visual Science [grant number P30 EY001319]; a grant from the Schmitt Program on Integrative Neuroscience (University of Rochester) to B.S. and B.Z.M; and an unrestricted grant from Research to Prevent Blindness to the Department of Ophthalmology at the University of Rochester.

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