

Reaching Out to See: Arm Position Can Attenuate Human Visual Loss

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Abstract

■ Electrophysiological recordings in monkeys have now revealed several brain regions that contain bimodal visuotactile neurons capable of responding to either tactile *or* visual stimuli placed on or near the hands, arms, and face. These cells have now been found in frontal, parietal, and subcortical areas of the monkey brain, suggesting a cortical network of neurons that preferentially represent near peripersonal space. The degree to which the visual responses of such cells rely on input from the primary visual cortex and the extent to which they may contribute to visual perception is not completely understood. Nonetheless, recent neuropsychological studies suggest that a similar representation of near space may be bimodally coded in humans as well. Given the accumulating evidence for specialized processing of visual stimuli placed near the hands and arms, we hypothesized that arm position may be capable of modulating human visual ability. Here we report the case of

WM, who lost his ability to see in his left visual hemifield after sustaining damage to his right primary visual cortex. Interestingly, the placement of WM's left arm into his "blind" field resulted in significantly better detection of left visual field stimuli compared to when his hand was placed in his lap at midline. Moreover, we found this attenuation to be confined to stimuli presented within reaching distance (unless a tool that extended WM's reach was held while he performed the test). These findings are highly consistent with the characteristics of the bimodal visuo-tactile neurons that have been described in monkeys. Thus, it seems that arm position can modulate human visual ability, even after damage to the primary visual cortex. This study provides an exciting bridge between monkey neurophysiology and human visual capacity while also offering a novel approach for improving visual defects acquired via cortical injury. ■

INTRODUCTION

Posterior cortical damage associated with strokes or other brain trauma frequently results in visual loss, such as hemianopsia—or the loss of sight in one half of the visual field. Unfortunately, these visual field defects are often considered permanent and therefore are *not* typically targeted for rehabilitation. In fact, such visual defects often persist, affecting a range of activities such as reading, cooking, and driving, thereby severely impacting a person's quality of life (Stelmack, 2001; Zihl, 2000). Here we report a case that indicates greater potential for the attenuation of human primary visual loss than has previously been considered.

Although various retinopathies have been intensely studied, few researchers have attempted to develop ways of restoring vision in patients whose visual loss was caused by cortical insult. German researchers, Kasten, Wuest, Behrens-Bamann, and Sabel (1998) and Kasten, Poggel, and Sabel (2000), have perhaps had the most success toward this goal. In essence, these researchers have demonstrated that repetitive visual stim-

ulation along boundaries of a field cut (or blind spot) can eventually increase the field of view by amounts of up to 5° of visual angle (approximately 5 cm viewed at arm's length) (Kasten et al., 1998). A major advantage of this computerized visual restitution program developed by Kasten et al. (2000) is that the improvements in visual detection have recently been found to generalize to both color and simple pattern recognition. However, the drawbacks of this technique are that extensive training is required (daily training over a 6-month period), and that the improvements are restricted to only a small portion of the visual field. Furthermore, this technique conveys the greatest benefits to patients whose visual loss is due to optic nerve damage (as opposed to cortical or white matter damage) (Kasten et al., 1998). Thus, visual loss associated with cortical damage, white matter damage, or both has still proven more difficult to restore.

Here we report the case of WM, who suffered a stroke that caused an infarction in his right posterior cerebral artery (PCA) including the right primary visual cortex. The stroke left WM with a severe left hemianopsia (i.e., unable to see in his left visual field). Upon close examination, it appeared that the severity of this gentleman's visual deficit varied with the position of his left arm, such that he reported seeing more of his left

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visual field when he used his own left arm to probe the area than when he was looking for an external item or an experimenter's hand. Given recent reports from the neurophysiological literature on specialized brain regions for coding visual space near the body, specifically visual stimuli located near the arms, hands, or face, we reasoned that a similar neuronal network might have been influencing WM's ability to see and detect visual stimuli in his impaired hemifield.

Single-unit recordings in monkeys have now revealed several brain regions that contain bimodal visuotactile neurons with corresponding visual and tactile receptive fields (Graziano, Hu, & Gross, 1997; Graziano, Yap, & Gross, 1994; Colby, Duhamel, & Goldberg, 1993; Graziano & Gross, 1993; Fogassi et al., 1992; Gentilucci, Scandolara, Pigarev, & Rizzolatti, 1983; Leinonen, Hyvarinen, Nyman, & Linnankoski, 1979). For example, bimodal neurons with tactile receptive fields located on hand, arm, or face also respond to visual stimuli placed within a certain distance of that same body part. Cells of this type have now been reported in frontal premotor cortex (Graziano et al., 1994, 1997; Fogassi et al., 1992; Gentilucci et al., 1983; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981), parietal areas 7b and VIP (Colby et al., 1993; Leinonen et al., 1979), and subcortically in the putamen (Graziano & Gross, 1993). Based on the properties of these neurons, including their neuroanatomical connections and their selectivity for visual stimuli presented within close range (approximately 20 cm) of a particular body part (Graziano & Gross, 1993; Fogassi et al., 1992; Rizzolatti et al., 1981), it is thought that these neurons may be responsible for the representation of space immediately surrounding the body (see Graziano & Gross, 1995). Moreover, monkeys with lesions in areas where visual-tactile cells have been reported evidently neglect stimuli located near the body while retaining their ability to detect stimuli located further away (Rizzolatti, Matelli, & Pavese, 1983). Finally, another important property of bimodal neurons that have tactile receptive fields on the hand or arm is that their *visual* receptive fields have been observed to change with the position of the arm in space (independent of gaze direction) (Graziano et al., 1994; Colby et al., 1993; Fogassi et al., 1992; Gentilucci et al., 1983). The visual receptive fields of these neurons are thus somatotopically rather than retinotopically defined.

In sum, single-unit recordings in monkeys have revealed several brain regions that contain neurons whose responsiveness to visual stimuli is dependent on the location of the stimulus with respect to the hand or arm. In light of this evidence for neurons that respond selectively to visual stimuli located near the hand/arm, we reasoned that arm position might be capable of attenuating human visual loss. Alternatively, it was possible that the apparent improvement in WM's vision in the left visual field (when his left arm was the probe) was restricted only to the view of his arm (perhaps based

on proprioceptive feedback) and would not necessarily generalize to visual stimuli placed near (but *not* in contact with) his arm. It was also possible that the active movement of his arm through the left visual field was what was responsible for his reportedly seeing better when looking for his own hand than when attempting to detect someone else's hand. Finally, if an actual improvement in visual detection were found, the electrophysiological findings would predict that this improvement would be limited to targets presented in near space, or within reaching distance, and would not generalize to targets presented further away.

To test these possibilities, we designed a computerized visual detection task to compare WM's visual detection abilities while varying the position of his left arm. First, we compared performance in a baseline condition (left arm in lap) with performance in an arm-out condition (left arm extended out into left visual field) while visual stimuli were presented at varying locations within reaching distance (60 cm). Next, we examined visual detection for identical stimuli placed well out of reach (180 cm), including a condition in which WM held a tennis racket in his extended left arm (essentially extending his effective reaching distance).

RESULTS

Baseline versus Arm Out

WM completed two baseline sessions (left arm in lap, see Figure 1A) and two arm-out sessions with his left arm extended out into the left visual field (Figure 1B). These sessions were alternately run and counterbalanced for order. As illustrated in Figure 1, in the baseline condition (Figure 1A) when his left arm was placed in his lap, WM correctly detected only 57/420 (13.6%) left visual field (LVF) probes and nearly all (97.8%) of the right visual field (RVF) probes. However, when WM's left arm was extended toward the LVF stimuli (Figure 1B), his detection of LVF targets almost doubled to 104/420 (24.8%). Meanwhile his overall RVF hit rate remained the same.

Although WM was verbally discouraged from guessing, the number of false alarms he made on *target-absent* trials (catch trials) afforded a means of estimating how often he might have been guessing or accidentally responding in a given session.¹ This was of special concern regarding his responses to targets presented within the defective left hemifield. Thus, WM's false alarm rate was calculated for each session² and was used to correct the number of LVF hits recorded for that session. The calculation used was as follows: [Corrected hit rate = (total hits) × (1-FA rate)]. Hence, a 20% false alarm rate would result in only 80% of the target-related button presses being counted as true hits.

Chi-square tests were then used to compare the number of targets detected (hits) in each visual field

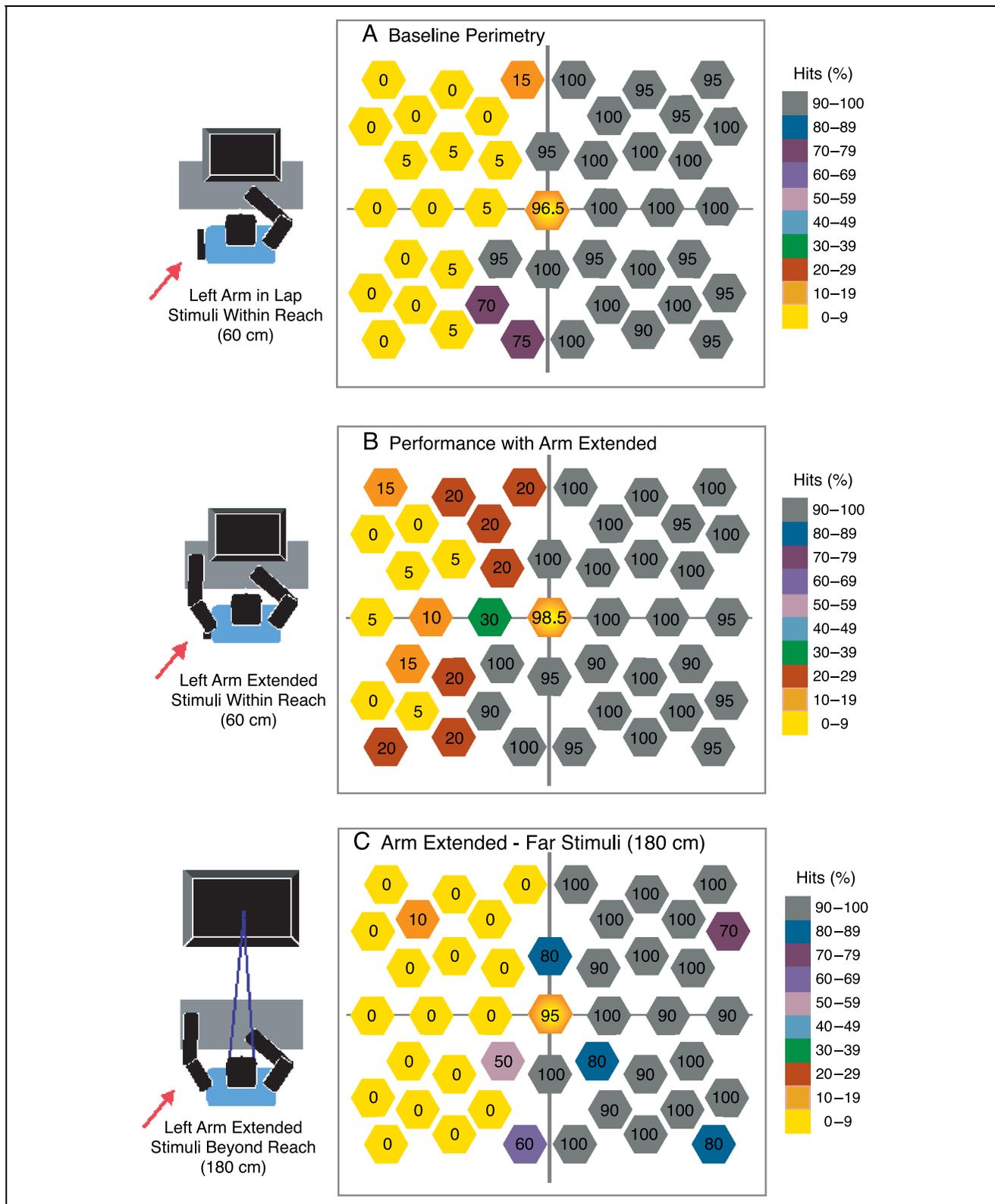


Figure 1. WM's performance on a computerized perimetry task indicated by the percent of targets detected at each of the possible locations (denoted by the peripheral hexagons). WM's accuracy (%) in reporting the central digit is shown in the central yellow-orange hexagon. Panel (A) shows WM's baseline (arm in lap) performance for stimuli presented within reaching distance. Note that yellow reflects locations where one or fewer targets were detected. Panel (B) illustrates WM's performance on the same task when his arm was extended out toward the stimulus display. Finally, panel (C) depicts WM's performance when his left arm was similarly extended, but the stimuli were presented well beyond reach.

across the two session types (baseline vs. arm out). Analysis of WM's corrected LVF hit rates revealed a significant improvement in left visual field detection in the arm-out condition compared to the baseline (arm in lap) condition, $\chi^2(3, n = 420) = 34.3, p < .01$. Additional analyses confirmed that this was the case even when analysis was restricted to just the first two sessions (baseline followed by arm out) or just the last two sessions (arm out followed by baseline), $\chi^2(1, n = 210) = 19.6$ and 14.7 , both $p < .01$.² In sum, LVF detection was reliably better in the arm-out compared to baseline condition, regardless of test order. In contrast, WM's detection of RVF targets did not vary as a function of session type, $\chi^2(3, n = 420) = 0$.

Far Condition

If neurons with arm-centered response properties like those described by Graziano and Gross (1993, 1995) and Graziano et al. (1994, 1997) are, in fact, contributing to WM's ability to detect LVF targets, then the benefit of arm extension should only occur for stimuli presented within reaching distance. On the other hand, if the improved detection is due to some sort of proprioceptive cue on the left side of space, then LVF targets placed at the same visual eccentricity but beyond reaching distance should also benefit. To test these predictions, the stimuli were magnified and projected onto a whiteboard 180 cm away (well outside of reaching distance), such that the probed locations spanned the same degree of visual angle as in the previous tests (see Figure 1C). Despite his arm being extended just as before (compare Figure 1B and C), WM's detection of LVF probes was significantly worse when the stimuli were placed beyond reach compared to the LVF stimuli placed within reaching distance, $\chi^2(1, n=210) = 22.8, p < .01$. Importantly, there was no difference in WM's detection of *right* visual field probes presented within as compared to beyond reaching distance, $\chi^2(1, n = 210) = 1.5, p > .05$. In other words, it seems that arm position only conveys a benefit to stimuli placed within reaching distance (Figure 1C).

Upper versus Lower Visual Field Comparisons

As can be seen in his baseline performance (Figure 1A), WM appears to have some visual sparing in the medial portion of his lower left quadrant. It turns out that this is consistent with his lesion. A CT scan of WM's brain shows complete infarction of the inferior calcarine cortex and substantial (albeit not necessarily complete) damage to the superior calcarine cortex (see Figure 2) of the right hemisphere. Because the representation of the visual field is inverted in the primary visual cortex, incomplete damage to the superior portion of the calcarine cortex could result in some visual sparing in

the lower left visual field, as seen in WM's baseline performance.

Thus, in order to examine whether the LVF enhancement observed for stimuli placed within reach was dependant on (or restricted to) this area of visual sparing, we separately analyzed WM's visual detection performance within the upper and lower visual fields (see Table 1a and b). A comparison of LVF hit rates when restricted to the nine positions of the lower left visual field revealed a significantly higher hit rate in the arm-out compared to baseline condition, $\chi^2(3, n = 180) = 9.0, p < .05$. More importantly, the same analysis when restricted to the nine positions of the *upper* left visual field, where visual sparing was less likely, also revealed a significantly higher hit rate in the arm-out condition, $\chi^2(3, n = 180) = 27.7, p < .01$.

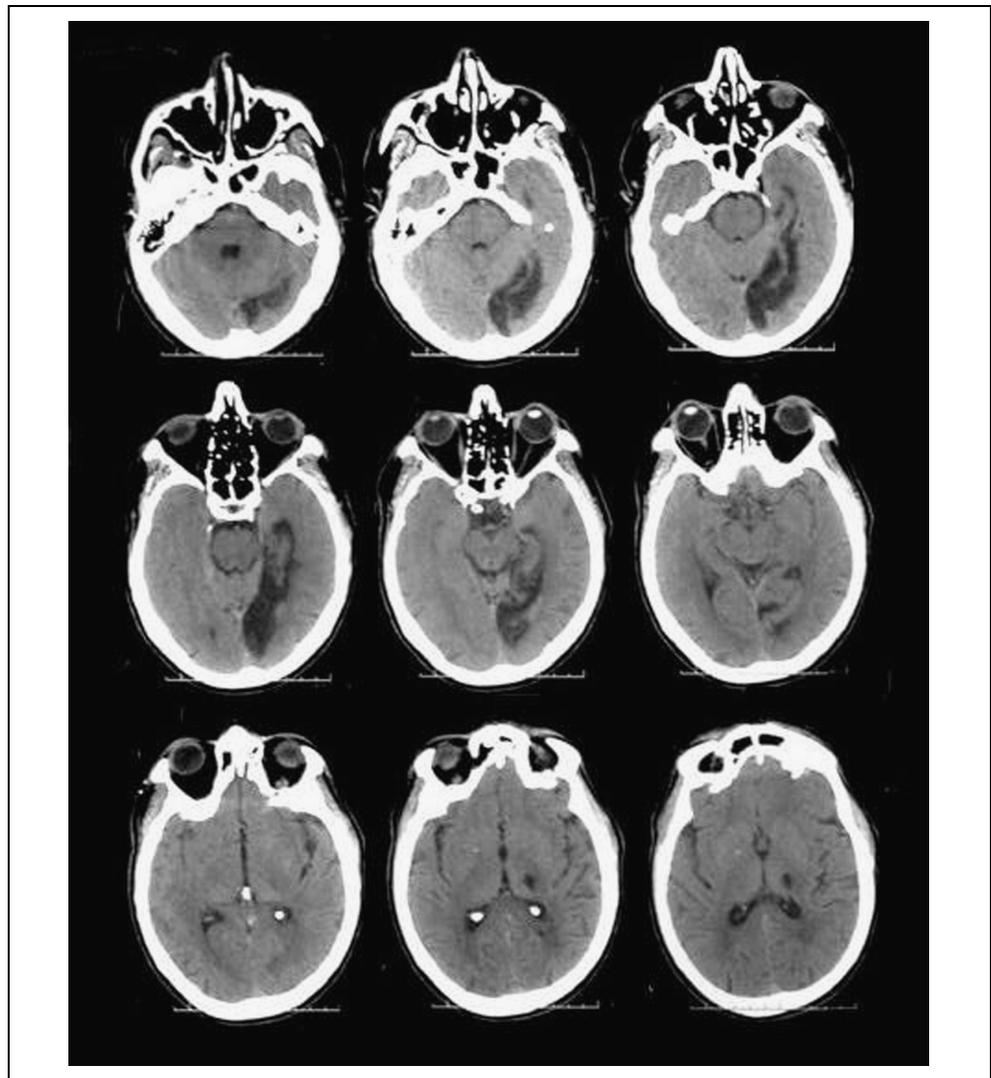
Finally, an analysis limited to the lower left visual field and omitting the three medial positions (where there was behavioral evidence of spared visual ability, see Figure 1A and B) also indicated significantly better detection in the arm-out condition compared to baseline, $\chi^2(3, n = 120) = 60.0, p < .01$. All together, these results suggest that arm-mediated visual enhancement was not confined to the region of greatest visual sparing. If anything, the effect appeared to be stronger in the *upper* rather than the lower visual field.

Far + Tool Condition

In a final test session, WM was given a tennis racket to hold in his extended left hand (nearly doubling the effective length of his arm) while stimuli were again presented from a distance of 180 cm (as in Figure 1C). Overall, WM detected a greater number of the far LVF targets ($33/210 = 15.7\%$) while holding the tennis racket than when just his arm alone was extended ($12/210 = 5.7\%$). Moreover, when the numbers of hits were corrected for false alarms and analysis restricted to the upper left visual field³ (see Table 1c and d), it was clear that the number of LVF hits was significantly greater with the tennis racket in hand than when his arm alone was outstretched, $\chi^2(1, n = 90) = 36.6, p < .01$. Although we were only able to conduct this condition one time and were thus unable to counter-balance testing order, the fact that WM's performance in the RVF did not differ between the *arm-only* and *arm + racket* conditions, $\chi^2(1, n = 90) = 1.6, p > .05$ strengthens this observation. Moreover, this observation is consistent with other observations in humans and monkeys alike, that tool use can result in a remapping or an extension of near peripersonal space.

Although the LVF improvement associated with the tennis racket in far space was not large (see Table 1), this could be due to at least two factors. First, even with the added length of the tennis racket, the far visual stimuli were still somewhat beyond reach. Second, in contrast to other studies on tool use, WM was only passively

Figure 2. Brain CT scan showing WM's right PCA infarct approximately 3 months poststroke. The right hemisphere is shown on the right.



holding the handle of the tennis racket and was not instructed to use it in any way.

DISCUSSION

In summary, a patient with primary visual field loss exhibited improved target detection in his contralesional

left visual field when his left arm was extended and placed within close range of the LVF probe stimuli. Interestingly, this arm-mediated visual improvement appeared to be limited to visual stimuli placed within reaching distance (60 cm), suggesting that the arm-mediated improvement in visual detection could not be explained by a proprioceptive cue alone. LVF detec-

Table 1. Percentage of Targets Detected as a Function of Experimental Condition (a–d) and Upper versus Lower Visual Field

	<i>Left Visual Field</i>		<i>Right Visual Field</i>	
	<i>Upper LVF</i>	<i>Lower LVF</i>	<i>Upper RVF</i>	<i>Lower RVF</i>
a) Baseline (near stimuli)	3 (3)	28 (27)	98	97
b) Arm out (near stimuli)	12 (11)	41 (38)	99	96
c) Arm out (far stimuli)	1 (1)	12 (12)	96	93
d) Arm + racket (far stimuli)	8 (8)	29 (29)	98	100

Values in parentheses are corrected for false alarms, and **bold face** indicates significant improvement in LVF detection.

tion remained impaired for more distant stimuli, unless he held a tennis racket in his outstretched hand, thereby extending his effective reaching distance.

With regard to the general finding that reaching out into the blind field attenuated this gentleman's visual loss, one could conceive of an attentional explanation by assuming that a greater amount of attention was deployed to the side of space containing the outstretched arm. This explanation, however, is unsatisfactory on the grounds that identical arm positioning did *not* significantly improve LVF detection when targets of equal retinal eccentricity were presented beyond reach. Furthermore, if more attention were allocated toward the side of space containing the outstretched arm, one might expect some decrement in performance in the opposite right visual field, but this was not the case. Additionally, attentional manipulations have not proven effective for ameliorating visual field defects, particularly when the defect is associated with damage to the primary visual cortex as was the case in WM.

Nevertheless, there is some evidence that hand position can enhance visual attention (Reed & Grubb, 2003; di Pellegrino & Frassinetti, 2000). Di Pellegrino & Frassinetti (2000) reported an attenuation of an attentional deficit known as visual extinction when a patient's fingertips were placed on the stimulus monitor adjacent to a to-be-reported visual stimulus (yet not when his hands were covered from view). Consistent with this finding, an ongoing study by Catherine Reed has presented evidence that healthy adults may also show increased attention to targets presented near an outstretched arm (Reed & Grubb, 2003). However, in each of these studies, the primary visual cortex was known to be intact, and there was no primary visual deficit in the sense that the participants were all able to detect individual stimuli presented to either visual hemifield. Furthermore, in the aforementioned studies, the participants could always see their outstretched hands, and in the case of the extinction patient, this proved to be critical.⁴ This was not the case for WM, who was unable to see his arm/hand when it was positioned as described in the Methods. Furthermore, extensive behavioral testing found no evidence of an attentional deficit in WM. Thus, the present study suggests that hand position can also ameliorate primary visual deficits associated with damage to primary visual cortex. Nonetheless, the extent and conditions under which hand position influences attentional selection versus primary visual processing warrant further research.

Following a stroke, it is difficult to confirm with certainty whether there may be some spared cortex within the area of infarction. In the case of primary visual cortex damage, such sparing might even be capable of supporting some residual visual ability such as in blindsight (see Fendrich, Wessinger, & Gazzaniga, 1992, 1993). The possibility of some cortical sparing, however, does not preclude the fact that WM's visual detection

varied as a function of arm position. Furthermore, highly reliable effects were observed when analysis was restricted to WM's upper left visual field where residual vision was less apparent (and cortical damage more complete). Also, in contrast to blindsight, where patients have been able to point or make eye movements toward stimuli presented in their blind spot when encouraged to *guess* the location of a stimulus that is not otherwise "consciously" perceived (see Weiskrantz, 1995), WM was asked to press a button whenever he *saw* the stimulus regardless of its location. Thus, while blindsight patients seem to exhibit some implicit spatial knowledge of stimuli that for one reason or another do not reach conscious awareness, WM was reportedly aware of the presence of the stimuli he detected (and his low false alarm rates attest to the fact that he was not simply guessing). Moreover, to our knowledge, visual detection in blindsight has never been shown to vary with the position of the subjects' limbs. However, there is no reason to assume that reaching out could not similarly improve vision in patients with blindsight, perhaps even bringing target stimuli into awareness.

The notion that visual stimuli presented near the hands may receive special processing in the human brain is consistent with reports in the neuropsychological literature. In particular, the idea that humans create and use hand-centered visual representations has been demonstrated in neurological patients with extinction. Extinction can be defined as an inability to bring a contralesional stimulus into awareness when a competing ipsilesional stimulus must be simultaneously processed. Consider a traditional example, where an extinction patient confidently detects a soft touch on her affected hand when it is presented alone, but is unaware of this same stimulus when the opposite (ipsilesional) hand is simultaneously touched. One might argue that this phenomenon could be explained by degraded sensory processing on the contralesional hand. However, a clever study conducted by Moscovitch and Behrmann (1994) tested 10 patients with left-sided extinction by simultaneously touching both the left and right sides of each patient's *unaffected* (ipsilesional) wrist while the patients' eyes were closed. Interestingly, the patients often failed to detect the stimulus presented on the leftmost side of their hand, indicative of extinction within a hand-centered representation.⁵ Moreover, the side that was extinguished also depended on the position of the hand. When the right palm was facing downward, extinction was observed on the thumb side of the wrist and when the palm was facing up, extinction was observed on the pinky side of the wrist. Thus, hand position critically influenced how somatosensory stimuli were being coded.

More recent studies in patients with extinction provide more direct evidence that the human brain does in fact integrate visual and tactile information presented within a certain distance of the hands and face (Ladavas,

2002; Ladavas, Zeloni, & Farne, 1998). Ladavas and colleagues have now reported several instances of cross-modal extinction in which a *visual* stimulus presented near the ipsilesional (unaffected) hand elicits the extinction (or suppression) of a *tactile* stimulus presented on the contralesional hand (Ladavas, 2002; Ladavas, di Pellegrino, Farne, & Zeloni, 1998; di Pellegrino, Ladavas, & Farne, 1997). Importantly, an identical visual stimulus at the same location in space does not elicit cross-modal tactile extinction in the absence of a nearby hand. Similarly, a visual stimulus that is presented too far above the ipsilesional hand also proves ineffectual in eliciting tactile extinction (Ladavas, 2002). Thus, it appears that it is the location of the visual stimulus with respect to the hand that is critical (and not merely its location in visual space). These findings imply that a visual stimulus presented *near* the hands is coded via the same neural mechanisms that code tactile stimulation *on* the hands. Thus, there is now tremendous agreement between behavioral observations in humans and single-unit recordings in monkeys that a network of bimodal visuotactile neurons may serve to commonly represent visual and tactile stimuli presented near the body.

Typically, peripersonal space refers to the space immediately surrounding the body, and it is understandable how stimuli near the body would be of particular relevance to an animal and may have thus come to be uniquely represented in the brain. But what exactly determines the extent of this imminent peripersonal space? It has been estimated that stimuli placed within 20 cm of the hand/arm elicit the strongest responses from bimodal neurons. In accord with this estimate, when WM's hand was placed along the left-most edge of the stimulus display, all of the LVF locations tested fell within 20 cm of his outstretched arm. Thus, it is not surprising that improved target detection was observed across multiple LVF locations (Figure 1B) instead of being localized to a specific portion of the visual field (such as the periphery or only at locations along the vertical meridian). Nevertheless, when stimuli of the same retinal eccentricity were displaced in depth, LVF detection remained impaired unless WM held a tennis racket in his outstretched hand. This is interesting for two reasons. For one, identical far stimuli were more likely to be detected when a potential reaching tool (tennis racket) was given to an otherwise identically positioned participant. Second, the fact that the racket seemed to have extended WM's range of near peripersonal space is highly consistent with electrophysiological studies on bimodal visual-tactile neurons in the parietal lobes of monkeys (Iriki, Tanaka, & Iwamura, 1996) as well as behavioral observations in patients with neglect (Berti & Frassinetti, 2000).

In two recent studies, Iriki and colleagues have provided evidence of the plasticity of bimodal receptive

fields in the monkey parietal lobe (Iriki et al., 1996; Iriki, Tanaka, Obayashi, & Iwamura, 2001). First they isolated several bimodal visual-tactile neurons and replicated previous findings that the visual receptive fields of these cells encompassed the area of space closely surrounding the hand, independent of gaze direction. They then trained the monkeys to use a rake in order to obtain food pellets that were placed beyond reach. After this training, the visual receptive fields of numerous bimodal neurons were remapped. Astonishingly, the visual receptive fields of roughly 30% of the cells had expanded to encompass the space along the length and immediately surrounding the rake (Iriki et al., 1996). More recently these researchers have shown that the visual receptive fields of these cells can even be remapped via training to include the space surrounding an *image* of the monkey's hand as viewed on a video monitor (Iriki et al., 2001). In fact, when the size of the hand was artificially changed on the monitor, the visual receptive fields were observed to contract or expand accordingly (Iriki et al., 2001). These results not only suggest that tool use can cause a remapping of near peripersonal space, but also indicate that the visual receptive fields of bimodal visual-tactile neurons have a tremendous amount of plasticity.

Of course, one methodological difference between the studies just described and the condition in which WM held a tennis racket was that in our study, the tennis racket (i.e., tool) served no task-relevant function. Instead of actively using the tennis racket to reach or point to the target stimuli, WM simply held it out towards the stimulus display.⁶ In fact, one might wonder why passively holding a tennis racket had any effect at all. We chose the tennis racket because WM reported being an avid tennis player since very early in his childhood. Thus, WM's extensive experience using a tennis racket may have constituted enough prior training to exhibit a tool effect akin to that observed in monkey bimodal neurons and the neglect patients who were, in contrast, actively using a tool to perform a task. This implies that more recent training or active use of the tool during the task may have augmented the degree of improvement observed in WM's visual detection ability in this condition. Unfortunately, we were unable to test this possibility.

Nevertheless, neuropsychological studies in patients exhibiting extinction and neglect have produced results that are highly consistent with neurophysiological evidence from monkeys for specialized processing of visual stimuli located near the hands and face. It appears that the underlying substrate of this processing relies on bimodal visual-tactile neurons that form visual receptive fields around relevant body parts, potentially even encompassing artificial extensions of the limbs (e.g., hand-held tools). However, the studies conducted in humans thus far have primarily demonstrated an effect of hand position on the perception of *tactile* stimuli

(Ladavas, 2002; Ladavas, di Pellegrino, et al., 1998; Ladavas, Zeloni, et al., 1998; di Pellegrino et al., 1997; Moscovitch & Behrmann, 1994). Until now, no one has tested the degree to which these nonretinotopic visual receptive fields may enhance or aid *primary visual ability* in humans. Here we report a case in which arm position attenuated a human primary visual field defect in near peripersonal space.

In sum, we report for the first time that arm position can attenuate visual loss following substantial damage to primary visual cortex. This attenuation may be due to responses from intact bimodal neurons of the type described in the neurophysiological literature (Graziano et al., 1994, 1997; Colby et al., 1993; Graziano & Gross, 1993; Fogassi et al., 1992; Gentilucci et al., 1983; Rizzolatti et al., 1981; Leinonen et al., 1979), suggesting that bimodal neurons with nonretinotopic visual receptive fields may be recruited to improve vision in cases of acquired visual loss. Although we cannot yet specify the precise neuroanatomical regions or pathways that may be necessary for such visual enhancement, the present findings provide a functional human correlate/analog to the arm-centered *visual* processing that has been observed in monkeys. Finally, the results also suggest that the primary visual cortex need not be completely intact for other visually responsive neurons to modulate vision, opening up a new avenue of exploration for restoring vision subsequent to brain damage.

METHODS

Participant

At the time of testing, WM was a 68-year-old, right-handed, male university professor who had sustained a stroke affecting his vision approximately 7 months prior. Neurological examination at the time of his stroke documented a dense left homonymous hemianopsia with no signs of an attention deficit such as neglect or extinction. A brain CT scan done 3 months after his stroke revealed a PCA infarct involving the right occipital lobe, including primary visual cortex, and extending forward into the temporal lobe and right hippocampus (see Figure 2), including a small area of infarction in the right thalamus. In reviewing the actual radiological films, a neurologist (who was not a part of the research study) concluded that the inferior portion of the calcarine cortex was completely infarcted and that there was also substantial damage to the superior portion as well.

We first met WM 6 months after his stroke when we conducted a full assessment for visual neglect and extinction (including line bisection, line cancellation, visual search, copying, reading, and drawing tasks). Consistent with the documentation in his medical charts, there were no signs of neglect or extinction.

Both visual confrontation testing and the computerized perimetry task confirmed a dense left hemianopsia.

Design and Procedure

To test the hypothesis that arm position was capable of attenuating WM's visual loss, we conducted several versions of a computerized perimetry (detection) task. Each test probed a total of 44 locations spanning 32° of horizontal visual angle (24° vertically). During *baseline* conditions, WM's left (contralesional) hand was placed in his lap, while his right hand was positioned at midline just in front of the computer so he could press the space bar whenever he detected a probe (an unfilled blue circle, subtending roughly 0.3° of visual angle). Stimuli were viewed from a distance of approximately 60 cm. During the *arm-out* condition, the stimuli and procedures were identical to those used in the baseline test with the exception that WM's left arm was placed on top of the table, resting on a pillow next to the left edge of the keyboard. In the *far* condition, WM's arm was similarly positioned on the tabletop, but the stimuli were magnified and projected onto a whiteboard 180 cm away, completely out of reach. Finally, in the *tool* condition, which was otherwise identical to the far condition just described, WM held a tennis racket in his extended left hand (arm and tennis racket resting on the table top).⁷

To ensure fixation at the center of the display, WM was instructed to keep his eyes just above a bar at the horizontal midpoint of the display and to report the Arabic numerals (1–9) subsequently presented there. Thus, WM performed a central report task concurrently with the peripheral detection task. Each target trial began with the fixation-only stimulus for 300 msec, followed by a central digit (duration 200 msec), followed by a peripheral probe (duration 150 msec). Probes were randomly presented at each of the 44 locations (denoted by hexagons in Figure 1), and the interstimulus interval between the central digit and the probe was kept very short (0 or 100 msec) to preclude the possibility of WM being able to foveate both the digit and the peripheral probe. Importantly, only trials in which the probe was detected AND the central number was correctly reported were counted as hits.⁸ Fifteen percent of the trials in each session were catch trials that were identical to the target trials except that no peripheral probe was presented.

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Notes

1. WM's false alarm rate (FA rate) was generally low (always less than 10%, and usually less than 5%).
2. Chi-square tests conducted on the noncorrected hit rates produced the same results.
3. The improvement in the lower visual field was primarily restricted to the locations in which WM appeared to have some residual vision. Thus, we chose to err on the conservative side and focus analysis on the upper visual field locations. Nonetheless, the degree of improvement in the lower visual field was substantial, as indicated in Table 1, Row (d).
4. A condition in which the extended hand was removed from view was not tested in the study by Reed and Grubb (2003).
5. The location of the hand with respect to the body was varied within subjects.
6. WM's left arm was too weak, and the task too long for this option to be considered.
7. The first baseline and arm-out sessions were conducted on separate days (baseline first followed by arm-out). The second time through, these two sessions were carried out in the same day, but in the opposite order (arm-out followed by baseline). Each session involving far stimuli was also carried out on a separate day (arm-out followed by arm + racket).
8. The maximum number of trials thrown out for erroneous digit report was $27/440 = 6\%$, and this occurred in the very first test session. In all subsequent tests, trials discarded for inaccurate digit report consisted of 5% or less.

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