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Absence of S-cone input in human blindsight following hemispherectomy

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Abstract

Destruction of the occipital cortex presumably leads to permanent blindness in the contralateral visual field. Residual abilities to respond to visual stimuli in the blind field without consciously experiencing them have, however, been described in cortically blind patients and are termed 'blindsight'. Although the neuronal basis of blindsight remains unknown, possible neuronal correlates have been proposed based on the nature of the residual vision observed. The most prominent but still controversial hypothesis postulates the involvement of the superior colliculi in blindsight. Here we demonstrate, using a computer-based reaction time test in a group of hemispherectomized subjects, that human 'attention-blindsight' can be measured for achromatic stimuli but disappears for stimuli that solely activate S-cones. Given that primate data have shown that the superior colliculi lacks input from S-cones, our results lend strong support to the hypothesis that 'attention-blindsight' is mediated through a collicular pathway. The contribution of a direct geniculo-extrastriate-koniocellular projection was ruled out by testing hemispherectomized subjects in whom a whole hemisphere has been removed or disconnected for the treatment of epilepsy. A direct retino-pulvinar-cortical connection is also unlikely as the pulvinar nucleus is known to receive input from S-cones as well as from L/M-cone-driven colour-opponent ganglion cells.

Introduction

Destruction of the occipital cortex leads to permanent blindness in the contralateral visual field and it has been presumed that this region is indispensable for vision. Residual visual function, however, has long been described in cortically blind patients (Bard, 1905; Pöppel *et al*., 1973) and the ability to respond to visual stimuli in the blind visual field without consciously experiencing them has been termed 'blindsight' (Weiskrantz *et al*., 1974, 1977; Weiskrantz, 1986; Shefrin *et al*., 1988). Although the existence of blindsight has been confirmed in numerous studies, the neuronal correlate of this phenomenon remains controversial.

The most prominent hypothesis is the involvement of the superior colliculi (see, for example, Weiskrantz, 1989; Sincich *et al*., 2004; Danckert & Rossetti, 2005). Electrophysiological studies indicate that the primate superior colliculus does not receive retinal input from short-wave-sensitive (S-) cones involved in colour vision, consequently rendering them colour blind to blue/yellow stimuli (Marrocco & Li, 1977; Schiller & Malpeli, 1977; Sumner *et al*., 2002; Savazzi & Marzi, 2004). The goal of this study was to demonstrate the absence of S-cone input in the blind visual field of hemispherectomized subjects with blindsight using psychophysical methods. We designed a computer-based reaction time test using achromatic black/white stimuli and blue/yellow stimuli (Fig. 1). These two stimulus types were designed and calibrated to isolate either the achromatic pathway or the blue/yellow colour pathway which draws on S-cones. To rule out previous criticism involving methodological limitations such as response bias (see, for example, Cowey, 2004; Ro *et al*., 2004), we used an approach in which the subjects respond only to consciously perceived stimuli in their sighted hemifield. In this kind of paradigm subjects are not aware of a stimulus presentation in their blind visual field, consistent with Weiskrantz's Type I blindsight classification [in contrast to blindsight with some awareness (Type II blindsight); Weiskrantz, 1989]; and the simultaneous presentation of an unseen stimulus in the blind hemifield can speed up the mean reaction time to the seen stimulus in the sighted hemifield. This spatial summation effect, in which reaction times to two bilaterally presented stimuli are significantly faster than to a single one, occurs in normal subjects and has previously been used to demonstrate the presence of unconscious visual function in the 'blind' hemifield of subjects with blindsight (Raab, 1962; Marzi *et al*., 1986; Tomaiuolo *et al*., 1997; Miniussi *et al*., 1998; Savazzi & Marzi, 2004). The spatial summation effect paradigm allows formulation of precise predictions about the type of visual information processed in the blind field of hemispherectomized subjects; specifically, if blindsight is mediated by the superior colliculi, only stimuli visible to the superior colliculus (achromatic) presented in the blind field will alter the reaction time to a consciously perceived stimulus in the normal visual field. Unconscious vision associated with implicit task interference effects of a stimulus presented in the blind visual field, as is the case in our paradigm, have also been named 'attention-blindsight' (for further details see Danckert & Rossetti, 2005).

We monitored eye movements with an eye tracking device and controlled for light scatter by using stimuli modulated about a uniform white background of the same mean luminance and chromaticity. Spared islands of visual cortex and all direct geniculo-extrastriate projections were ruled out by testing hemispherectomized subjects whose surgery involved removal or disconnection of an entire cerebral

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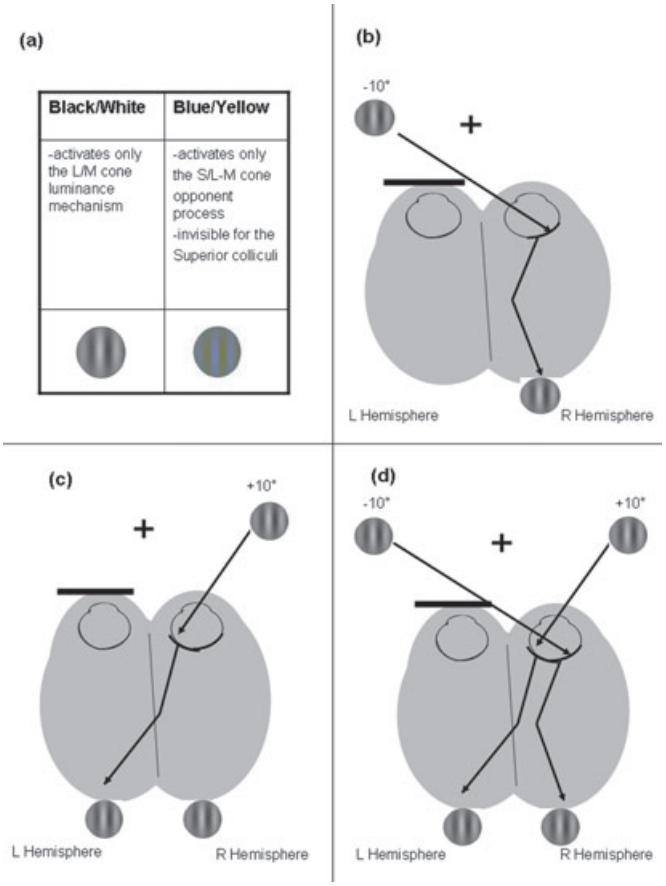

FIG. 1. Position of stimulus presentation (Left eye occluded). (a) Examples of stimuli used (achromatic; blue/yellow). (b) Unilateral 10° Left (presentation at −10°). Left eye is occluded, and the right eye is fixating a central fixation point. A stimulus is presented at 10° left of the central fixation point. Visual information is processed in the right hemisphere. (c) Unilateral 10° Right (presentation at +10°). Left eye is occluded, and the right eye is fixating a central fixation point. A stimulus is presented at 10° right of the central fixation point. Visual information is processed in the left hemisphere. (d) Bilateral 10° (presentation at ±10°). Left eye is occluded, and the right eye is fixating a central fixation point. Two stimuli are presented simultaneously at 10° left and right of the central fixation point. Visual information reaches both hemispheres.

hemisphere including the occipital lobe, leaving the patient with a contralateral hemianopia without macular sparing (Fig. 2).

We included two groups of hemispherectomized subjects, one with and the other without documented blindsight. A comparison of the two groups enabled us to determine the possible role of external factors such as light scatter and stimulus fixation. In addition, because the pulvinar is known to receive input from all classes of colour-opponent ganglion cells (L/M- as well as S-cone driven) (Felsten *et al*., 1983; Cowey *et al*., 1994; Barrett *et al*., 2001), our results allowed us to exclude the possibility that, at least in hemispherectomized subjects, blindsight is mediated by a direct contralateral retino-pulvinar connection.

Methods

The study was approved by the Montreal Neurological Institute & Hospital (MNI) Research Ethics Committee. All subjects gave informed consent.

Normal subjects

Sixteen normal subjects, who had no history of neurological and ophthalmological diseases, and had normal or corrected-to-normal acuity, were recruited and age matched (ages between 20 and 46 years; mean ± SD = 30 ± 6.8 years) to the hemispherectomized subjects.

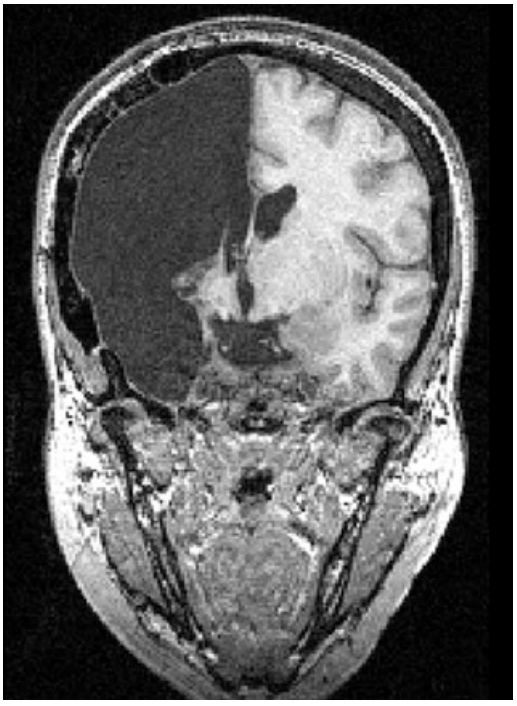

FIG. 2. Example of anatomical MRI of a participating hemispherectomized subject (DR).

Hemispherectomized subjects

Five postoperative hemispherectomy patients, who had their surgery performed at the McGill University Health Centre (MUHC), were recruited. They had participated in other blindsight experiments in the past. All subjects underwent neuroophthalmological examination and had normal colour vision, regular intraocular media, normal or corrected-to-normal acuity and a well-documented hemianopia without macular sparing. Anatomical scans showed preservation of both superior colliculi, but only the presence of the pulvinar and LGN on the healthy side.

All subjects were classified into a 'with blindsight' (subjects DR, SE, LF) or 'without blindsight' group (subjects FD, JB) according to their performance on previous spatial summation tasks and imaging studies carried out in our laboratories (for further details on subjects see Table 1 and Tomaiuolo *et al*., 1997; Bittar *et al*., 1999; Leh *et al*., 2003, Cognitive Neuroscience Society, Annual Meeting, New York, USA; Leh *et al*. 2004, Cognitive Neuroscience Society, Annual Meeting 2004, San Francisco, USA; Leh *et al*., 2006a, b).

Hemispherectomy; clinical history

DR

DR is a right-handed woman (32 years old at the time of testing) who had a left hemiparesis since birth. Epileptic seizures started at age 5 years. A severe atrophy of the right cerebral hemisphere was revealed by CT and MRI scans. At 17 years, she underwent a functional hemispherectomy which involved removal of the temporal lobe (including the mesial structures), the amygdala and hippocampus and a frontal–parietal corticectomy. The remaining cortical regions

TABLE 1. Demographic data of participating hemispherectomized subjects

Subject	Sex	Aetiology	Surgery type	Side	Age (years)	Blindsight
SE	Male	Right porencephalic cyst	Partial hemispherectomy	R	40	Yes
DR	Female	Rasmussen's encephalitis	Functional hemispherectomy	R	31	Yes
LF	Male	Arterio-venous malformation	Functional hemispherectomy	R	41	Yes
JB	Male	Left porencephalic cyst	Functional hemispherectomy	L	40	No
FD	Female	Meningitis, right middle cerebral artery infarct	Functional hemispherectomy	R	23	No

were left *in situ* but were disconnected from the rest of the brain by sectioning the white matter anteriorly and laterally as well as posteriorly and laterally along the falx. Subsequent neuropathological investigation revealed an inflammatory process with diffuse gliosis, consistent with chronic Rasmussen encephalitis. MRI scans postoperatively showed the presence of the right and left superior colliculi, but only the pulvinar on the left side.

SE

SE is a right-handed man who was 40 years old at the time of testing. A left hemiparesis was first noted at the age of 6 months and seizures started at the age of 7 years. A CT scan revealed a large porencephalic cyst in the right temporo-parietal area. At the age of 25 years, a temporo-parieto-occipital lobectomy including the amygdala and hippocampus and sparing the anterior portion of the frontal lobe was carried out. Remaining parts of the occipital lobe were disconnected from the rest of the brain. Postoperative neuropathological examination revealed a neuronal migration disorder (cortical dysplasia). MRI scans postoperatively showed the presence of the right and left superior colliculi, but only the pulvinar on the left side.

LF

LF is a right-handed man who was tested at the age of 41 years. At age 19 years, an arterio-venous malformation was partially resected. Seizure onset was at age 22 years. At 26 years, a temporal–parietal–occipital lobectomy was performed including an excision of the malformation in the occipital lobe, hippocampus and amygdala.

FD

FD is a right-handed woman who was tested at the age of 23 years. She had a history of epilepsy since age 1 year secondary to meningitis and a right middle cerebral artery infarct. At age 18 years, a right functional hemispherectomy including a resection of the amygdala and hippocampus was performed. This surgery included a pericallosal and frontal basal disconnection. MRI scans postoperatively showed the presence of the right and left superior colliculi, while only the pulvinar on the left side was present.

JB

JB is a left-handed man who was tested at the age of 40 years. He had a right hemiparesis since birth. Epileptic seizures developed at the age of 5 years. A CT scan of the brain demonstrated severe atrophy of the left hemisphere and the presence of a porencephalic cyst. A partial hemispherectomy was initially performed. This consisted of a temporal–parietal corticectomy and disconnection of the frontal lobe from the rest of the brain. Neuropathological investigation revealed neuronal loss and moderate to severe gliosis of unknown aetiology. Because of persisting epileptic seizures, a second surgical intervention was performed 3 months later. The functional hemispherectomy was then completed by adding a temporal lobectomy (including the mesial structures), a hippocampectomy and a partial occipital lobectomy which left the occipital pole *in situ* but disconnected from the white matter. Neuropathological examination revealed neuronal loss in both neocortex and hippocampus. MRI scans postoperatively showed the presence of the right and left superior colliculi, but only the pulvinar on the left side.

Experimental design

Stimuli

The stimuli consisted of achromatic and blue/yellow gabor patches set in a uniform background of the same mean luminance and chromaticity. Each vertical gabor element is described by:

$$G(x, y) = L_{\mathrm{p}}(1 + c \times \sin(2\pi f x) \times \exp((-x^2 + y^2)/2\sigma^2))$$

where (x,y) is the distance in degrees from the element centre, c is the Michelson contrast and L is the mean quantal catch of the L-, M- and S-cone types with respect to the white background. The sinusoidal frequency f is 1 cycle per degree, and the space constant (σ) is 1 degree. The mean luminance of the stimulus was 19 cd/m^2. Stimuli were presented with a temporal Gaussian contrast envelope of $s = 250$ ms at a viewing distance of 60 cm.

Colour space

The chromaticity of the stimuli was defined using a three-dimensional cone contrast space in which each axis represents the quantal catch of the L-, M- and S-cone type normalized with respect to the white background (i.e. cone contrast). Stimulus chromaticity and contrast is given by a vector direction and magnitude, respectively, within the cone contrast space, and is device independent. S-cone isolating and achromatic stimuli were determined within this space to isolate the S-cone opponent chromatic pathway (blue-yellow) and the achromatic pathway, respectively. Each of the stimulus types isolates one postreceptoral mechanism and is invisible to the others. We selected our cardinal stimuli from the knowledge of the cone weights of the three postreceptoral mechanisms provided by earlier studies (Cole *et al.*, 1993; Sankeralli & Mullen, 1996, 1997), and they have the following directions in the cone contrast space given by the relative L-, M- and S-cone weights: 1, 1, 1, respectively, for the achromatic stimulus and cone weights of 0, 0, 1, respectively (the S-cone axis) for the blue/yellow stimulus.

Prior to the actual experiment, detection thresholds for the blue/yellow and the achromatic stimuli were measured using a temporal two-way forced choice staircase procedure in three normal subjects in order to test reaction times for both stimuli under equivalent conditions, and were based on the mean of three staircase runs. The temporal presentation was Gaussian modulated with a σ of 250 ms. The psychophysical staircase was run using a two-interval forced choice paradigm in which the stimulus contrast was decreased after two correct

responses and increased after one wrong response. It was decreased by 50% after the first reversal and by 25% thereafter. The session was terminated after six reversals and the threshold calculated as the mean of the last five reversals, corresponding to a threshold value of 82% correct on the psychometric function. The mean contrast threshold for achromatic gratings was 0.03 and for blue/yellow gratings 0.06. For our experiment we used a contrast of 10 times contrast threshold (0.3 for achromatic stimuli, 0.6 for blue/yellow stimuli). In the case of the S-cone gratings this is the maximum physical contrast and is limited by the spectral overlap of S- with L- and M-cones and the red, green and blue phosphors of the CRT display monitor.

Apparatus and calibration

Stimuli were generated using a VSG 2/5 graphics board with 15 bits of contrast resolution (Cambridge Research Systems Ltd, Rochester, UK), housed in a Pentium PC computer displayed on a CRT monitor (Diamond Pro 2030, Mitsubishi). The spatial resolution of the screen was 1024 × 768 pixels. The red, green and blue spectral emissions of the CRT phosphors were measured using a PhotoResearch PR-650-PC SpectraScan (Chatsworth, CA, USA) and the Smith & Pokorny fundamentals (Smith & Pokorny, 1975) were used for the spectral absorptions of the L-, M- and S-cones. From these data, a linear transform was calculated to specify the red, green and blue phosphor contrasts required for given L-, M- and S-cone contrasts (Mullen & Kingdom, 2002). The display was gamma corrected in software lookup tables.

General procedures

The subjects participated in a computer-based reaction time task. Head movements were minimized with a chin rest and the left eye was covered with an eye patch. An eye tracking system (Quick Glance 2SH, Eye Tech Digital Systems, Mesa, AZ, USA) was used to control for eye movements and to ensure stimulus lateralization. Each run started with the subject having to maintain fixation for at least 5 s. The study was discontinued if the subject was not able to maintain fixation over this period.

During the experiment, the subject fixated a cross in the centre of the display screen while stimuli appeared on the left and/or right side of the fixation point (Fig. 1). Each stimulus was presented at three positions in a randomized order at: +10° unilaterally, −10° unilaterally or ±10° bilaterally. Five null events were included in order to minimize biased responses. Each experimental condition consisted of five blue/yellow and five achromatic stimulus presentations, 35 stimuli presentations in all. Stimuli were presented with a randomized stimulus onset time of 0, 500 or 1000 ms with an interstimulus interval of 2000 ms. The participant was asked to respond to the consciously perceived stimuli by pressing a mouse button as quickly as possible. Eye movements were monitored during the whole experiment and trials with movements greater than 3° away from the fixation point were discarded. Every control subject completed six runs of the experiment, and every hemispherectomized subject completed 25 runs to reduce their higher variability.

The study consisted of three parts. In an initial control experiment, 16 normal subjects were recruited and mean reaction times were measured for monocularly presented achromatic and blue/yellow gabor patches at either +10° (right visual field), −10° (left visual field) or ±10° (both visual fields) to demonstrate that the spatial summation effect can be mediated by both a blue/yellow and an achromatic pathway in the normal visual system (Fig. 1). In the second experiment we applied the same paradigm on three hemispherectomized subjects who have blindsight as demonstrated in previous studies (Table 1; subjects DR, SE and LF). In a third experiment, we applied the same paradigm on two hemispherectomized subjects who had not shown blindsight in previous studies (Table 1; subjects FD and JB). This group was chosen to control for the effects of light scatter. No alteration in their reaction times by the presentation of a stimulus in their blind visual field would effectively rule out light scatter as a possible explanation for the spatial summation effect observed in hemispherectomized subjects with blindsight.

Results

Spatial summation effect in normal subjects

Average reaction times for each control subject were entered into a 2 × 3 repeated-measures ANOVA with colour (blue/yellow, achromatic) and position (Unilateral 10° Right, Unilateral 10° Left, Bilateral 10°) as within-subject factors (Fig. 3A). This analysis revealed a significant main effect of position ($F_{1,15} = 23.37$, $P < 0.001$) and a significant main effect of stimulus colour ($F_{2,14} = 36.47$, $P < 0.001$), and no significant interactions between the two factors ($F_{2,14} = 0.71$, $P \leq 0.5$). Subjects detected the presence of two stimuli significantly faster than one (spatial summation effect), regardless of colour or spatial position (bilateral compared with Left, $P < 0.001$; bilateral compared with Right, $P \leq 0.005$). No difference of reaction times between unilateral left and right were found ($P = 1.00$). Furthermore, they showed faster reaction times to isochromatic black/white stimuli compared with isoluminant blue/yellow stimuli.

The results confirm that a spatial summation effect across the vertical meridian can be observed for blue/yellow as well as achromatic stimuli in normal subjects (Fig. 3A). These findings show that in the normal visual system spatial summation can be supported by both a blue/yellow chromatic and an achromatic pathway and demonstrate that this summation effect in normal subjects is not selective for particular visual pathways.

Spatial summation effect in hemispherectomized subjects with blindsight

Hemispherectomized subjects only reacted to stimuli presented in their normal visual field (right visual field) and not to stimuli in the blind field. We conducted *t*-tests on each subject between ipsilateral unilateral 10° right and bilateral 10° conditions for blue/yellow and achromatic stimuli separately (Fig. 3B). DR, LF and SE showed significant faster reaction times when achromatic stimuli were presented bilaterally at 10° compared with unilaterally at 10° to the right (spatial summation effect) (DR: $t \leq 0.001$, d.f. = 24; LF: $t \leq 0.05$, d.f. = 24; SE: $t \leq 0.05$, d.f. = 24). Reaction times were not faster to blue/yellow stimuli presented bilaterally at 10° compared with unilaterally at 10° to the right (no spatial summation) (DR: $t = 0.36$, d.f. = 24; LF: $t = 0.73$, d.f. = 24; SE: $t \leq 0.5$, d.f. = 24). A 2 × 2 repeated-measures ANOVA on each of the three subjects also showed faster reaction times to achromatic stimuli than to blue/yellow stimuli (DR: $F_{1,24} = 8.31$, $P \leq 0.01$; LF: $F_{1,24} = 51.07$, $P \leq 0.001$; SE: $F_{1,24} = 140.68$, $P \leq 0.001$).

The three hemispherectomized subjects with blindsight showed a spatial summation effect to achromatic stimuli in their sighted hemifield, even though the second stimulus was presented to their blind visual field (Fig. 3B) and was undetected. These results support the existence of 'attention-blindsight' ('Type I' blindsight) in these subjects and confirm previous results with hemispherectomized subjects (Tomaiuolo *et al*., 1997). Presentation of the blue/yellow stimulus in the blind visual field of these subjects, however, failed to

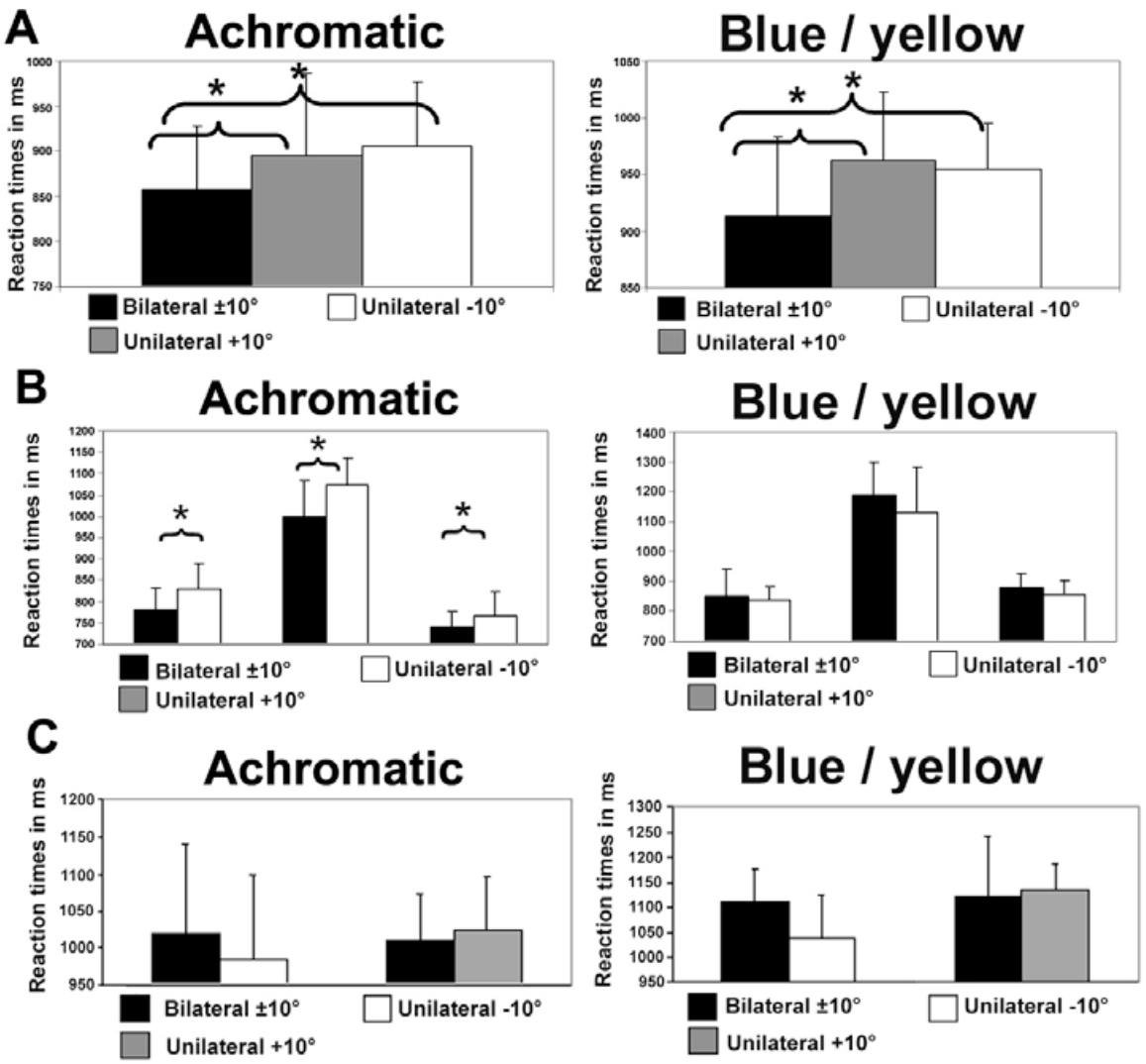

FIG. 3. Spatial summation effect. (A) Normal subjects. A significant spatial summation effect was observed independently of colour ($n = 16$, $F_{1,15} = 23.37$, $P < 0.001$). (B) Hemispherectomized subjects with blindsight ($n = 3$, DR, LF, SE). A spatial summation effect was observed for achromatic stimuli ($n = 2$, DR: $t \leq 0.001$, d.f. $= 24$; LF: $t \leq 0.05$, d.f. $= 24$; SE: $t \leq 0.05$, d.f. $= 24$), but not for blue/yellow stimuli (DR: $t = 0.36$, d.f. $= 24$; LF: $t = 0.73$, d.f. $= 24$; SE: $t \leq 0.5$, d.f. $= 24$). (C) Hemispherectomized subjects without blindsight (FD, JB). No spatial summation effect was observed for either achromatic or blue/yellow stimuli (achromatic: FD: $t = 0.20$, d.f. $= 24$; JB: $t = 0.61$, d.f. $= 24$; blue/yellow: FD: $t = 0.14$, d.f. $= 24$; JB: $t = 0.34$, d.f. $= 24$). Note that all subjects were tested with the right eye, while the left eye was occluded. An asterisk indicates significant difference.

alter their reaction time, demonstrating that their blindsight is colour-blind specifically for blue/yellow stimuli.

Spatial summation effect in hemispherectomized subjects without blindsight

These hemispherectomized subjects only reacted to stimuli presented in their normal visual field (for right hemispherectomized subject: right visual field; for left-hemispherectomized subjects: left visual field). We conducted *t*-tests on each subject between ipsilateral unilateral at 10° presentations (Right for FD, and Left for JB according to their hemispherectomized side) and bilateral at 10° conditions for blue/yellow and achromatic stimuli, respectively (Fig. 3C). FD and JB showed no significant difference on reaction times between bilateral at 10° and ipsilateral unilateral at 10° (Right for FD, and Left for JB) conditions for achromatic (FD: $t = 0.20$, d.f. $= 24$; JB: $t = 0.61$, d.f. $= 24$) and blue/yellow (FD: $t = 0.14$, d.f. $= 24$; JB: $t = 0.34$, d.f. $= 24$) stimuli (no spatial summation). A 2×2 repeated-measures ANOVA on JB showed faster reaction times to achromatic stimuli than to blue/yellow stimuli (JB: $F_{1,24} = 28.45$, $P \leq 0.001$). FD demonstrated a tendency towards faster reaction times to achromatic stimuli without reaching a statistically significant level.

For these two hemispherectomized subjects who also had not shown blindsight in previous studies (subjects FD and JB), the presentation of a second stimulus in their blind visual field, either achromatic or blue/yellow, did not alter the reaction time to the consciously perceived stimulus in their normal visual field (Fig. 3C). These results demonstrate that the spatial summation effect obtained in hemispherectomized subjects with blindsight is not due to light scatter, inadequate fixation or criterion effects, as none of the hemispherectomized subjects without blindsight demonstrated a significant spatial summation effect. Furthermore, our stimuli are likely to exclude light scatter as a potential artefact because gabor patches are modulated about a uniform white background of the same mean luminance and chromaticity. The possibility of inadequate

fixation to explain our results is also not tenable as we controlled for eye movements with an eye tracking system as well as fast (Gaussian contrast envelope of $s = 250$ ms) and simultaneous bilateral stimulus presentation. Finally, the possibility of spared islands of the visual cortex subtending the residual visual abilities is not justifiable because all our hemispherectomized subjects had a well-documented hemianopia without macular sparing and all of their occipital lobe had been either removed or disconnected from the rest of the brain as established with the operation reports and magnetic resonance imaging.

Reaction times to blue/yellow vs. achromatic stimuli

We observed slower reaction times to blue/yellow gratings than to achromatic gratings, which is in accordance with previous studies that examined processing time and temporal properties of the S-cone opponent colour system and found a 'sluggishness of the S-cone system' (Beaudot & Mullen, 2001; McKeefry *et al*., 2001, 2003; Smithson & Mollon, 2004). Our results are thus consistent with physiological studies demonstrating that information processing to the primary visual cortex mediated by S-cones is slower than information processing subtended by the L/M-cone system (Cottaris & DeValois, 1998).

Discussion

We have shown that, in the normal visual system, spatial summation can be mediated by both a blue/yellow (S-cone) and an achromatic pathway. By contrast, hemispherectomized subjects with blindsight demonstrated a spatial summation effect to achromatic stimuli only, suggesting that their blindsight is colour-blind specifically to blue/yellow stimuli and is not receiving input from retinal S-cones. Moreover, their response to achromatic stimuli cannot be accounted for by light scatter as no response was found in our control group of hemispherectomized subjects without blindsight.

Hemispherectomy comprises the surgical removal or disconnection of an entire cerebral hemisphere and therefore excludes the possibility that the effect may be explained by spared islands of visual cortex or by geniculo-extrastriate pathways. Consequently, visual information in the blind visual field of these subjects can only be processed via either the ipsilateral superior colliculus or the contralateral pulvinar on to the remaining hemisphere.

The pulvinar is known to receive input from all classes of colour-opponent ganglion cells (L/M- as well as S-cone opponent) (Felsten *et al*., 1983; Cowey *et al*., 1994) and was shown to be involved in colour processing in humans (Barrett *et al*., 2001). By contrast, electrophysiological studies demonstrate an absence of retinal input from S-cones involved in blue/yellow colour vision to the superior colliculus, therefore rendering collicular cells colour-blind to blue/yellow stimuli (Marrocco & Li, 1977; Schiller & Malpeli, 1977; Sumner *et al*., 2002; Savazzi & Marzi, 2004). This S-cone system seems to be conserved across mammals (Calkins, 2001). As we were able to demonstrate the absence of S-cone input in the blind visual field of hemispherectomized subjects, it follows that our results strongly suggest that blindsight (at least following hemispherectomy) is mediated by the superior colliculus.

Unconscious vision associated with implicit task interference effects of a stimulus presented in the blind visual field, such as the spatial summation effect, has previously been associated with a collicular pathway [for further details see also 'Type I' blindsight (Weiskrantz, 1989; Tomaiuolo *et al*., 1997) and 'attention-blindsight' (Danckert & Rossetti, 2005)]. An animal model of hemispherectomy has demonstrated that the ipsilateral superior colliculus in the vervet monkey is much less affected than that of the dorsal lateral geniculate nucleus after neonatal hemicorticectomy (Ptito *et al*., 1996). Previous anatomical studies on the superior colliculus connectivity demonstrated excitatory and inhibitory intercollicular connections (Olivier *et al*., 2000; Rushmore & Payne, 2003) and suggested that removal of inhibitory connections between the two superior colliculi can lead to restored vision in animals (Sewards & Sewards, 2000). In a recent diffusion tensor imaging tractography study, we demonstrated a significant correlation between the strength of collicular tracts and the presence of 'attention-blindsight' ('Type I' blindsight) in hemispherectomized subjects (Leh *et al*., 2006a). In that study, 'attention-blindsight' subjects showed strong projections from the superior colliculus of the hemispherectomized side to areas of the contralateral remaining hemisphere. These areas included primary visual areas, visual association areas, the posterior internal capsule, prefrontal areas, parietal areas and an area close to the frontal eye fields. These connections were not seen in hemispherectomized subjects without blindsight.

Previous research was unable to demonstrate unequivocally colour sensitivity in blindsight (Stoerig & Cowey, 1989). Most of the previous studies on wavelength discrimination examined subjects with smaller lesions that did not exclude all geniculo-extrastriate pathways, which receive input from all ganglion cell classes including input from the blue/yellow system, and/or a role for spared islands of the visual cortex. None of these studies examined hemispherectomized subjects. The methods used were variable and included, for example, measurements of pupil constrictions (Weiskrantz *et al*., 1999), forced choice paradigms (Weiskrantz *et al*., 2002b), flanker tests (Danckert *et al*., 1998) as well as after-images (Weiskrantz, 2002a) in response to different coloured stimuli presented in the blind field of the subject. These studies mainly presented red and green stimuli at different wavelengths that did not isolate the luminance system from the red/green or blue/yellow opponent colour systems.

The existence of several types of unconscious vision has been demonstrated in numerous studies, and their neuronal correlates have been hypothesized according to the nature of the residual vision observed (Weiskrantz, 1989; Danckert *et al*., 1998). Consistent with Danckert *et al*.'s (1998) theory and our study, geniculo-extrastriate pathways seem to be necessary for unconscious wavelength- and form-discrimination abilities. Further studies are therefore needed to investigate colour opponent mechanisms in blindsight subjects with circumscribed lesions.

In summary, our results in hemispherectomized subjects are consistent with the existence of 'attention-blindsight' ('Type I' blindsight) and an absence of S-cone input. This is in keeping with our hypothesis that blindsight in hemispherectomized subjects is mediated by the superior colliculus with its connections to the remaining hemisphere being essential to support unconscious processing of visual information.

Conclusion

We have demonstrated a significant spatial summation effect in normal subjects through S-cone-dependent and -independent pathways. In hemispherectomized subjects with 'attention-blindsight' ('Type I' blindsight), we were able to show an absence of S-cone input in the blind visual field by demonstrating a significant spatial summation effect only with achromatic stimuli but not with S-cone isolating (blue/yellow) stimuli. These results strongly support the hypothesis

that visual information in the blind visual field of these subjects is processed by a collicular pathway that does not receive any input from retinal S-cones, consequently making it colour-blind to blue/yellow stimuli.

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Competing interests statement

The authors declare that they have no competing financial interests.

Abbreviation

S-cones, short-wave-sensitive cones.

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