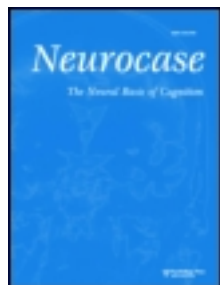


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# Occipital cortex activation by long-term repetitive tactile stimulation is necessary for object recognition in blinds: A case report

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Tactile vision has been approached from a variety of angles using different techniques. So far, a certain kind of object (and text) recognition has been shown, though seeing as such has not been achieved yet, and it remains unclear. Trough repetitive passive tactile stimulation perceptual processing is transferred from temporo-parietal to occipital areas, which affects object recognition. We report the results of passive tactile stimulation, as well as rTMS, applied to a 50 year old left handed blind male with over 97% loss of vision, who suffers from Peter's anomaly and microphthalmia. After 15 weeks of passive tactile stimulation, the subject showed increased activity in occipital areas associated with the development of visual-like perception which remained unchanged after three months without passive tactile stimulation. Inhibitory rTMS over the visual cortex led to noticeable reduction of spatial recognition performance and visual sensations in this subject. Stable changes in occipital cortical activity can be associated with subjective sensations of seeing. Once occipital activation has been achieved, it is necessary for spatial object recognition. Both facts highlight the implication of occipital areas in tactile vision and the cortical plasticity of passive tactile long-term stimulation in people with blindness.

**Keywords:** Blind; Cortical plasticity; ERP; Passive tactile stimulation; rTMS.

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Cross-modality in blind subjects allows “colonization” of visual-related areas by auditory or tactile stimuli (Theoret, Merabet, & Pascual-Leone, 2004). Regular passive cross-modal stimulation in blind people may lead to a greater connectivity in occipital areas after twelve weeks (Ortiz et al., 2011), and specifically to activation of visual areas after tactile stimulation (Gizewski, Gasser, de Greiff, Boehm, & Forsting, 2003; Sadato et al., 1996); a finding also reported in normal seeing individuals (Merabet et al., 2008).

Cortical plasticity is a process in which neurons increase or decrease their interconnections modulating their strength as a consequence of experience, learning and sensory and cognitive stimulation (Feldman & Brecht, 2005). Ramón y Cajal (1904) postulated that stimulation makes possible “the formation of new pathways through ramification and progressive growth of dendrite arborisation and nerve terminals, besides reinforcement of pre-established organic pathways.” Along this line of thought, Pascual-Leone et al. (2005) consider that neuronal plasticity can only be accomplished through reinforcement of pre-existing connections.

Different authors have documented the existence of remapping of cross sensory stimuli towards other sensory areas, mainly visual, in people with blindness, something more prominent with tactile stimulations during the infantile years (Ortiz et al., 2010). Remapping towards occipital areas increases progressively with training when the initial stimulation is tactile (Ortiz et al., 2011; Poirier, De Volder, & Scheiber, 2007) or auditory (Gougoux, Zatorre, Lassonde, Voss, & Lepore, 2005).

Animal studies have shown connections between A1 to V1, as well as multi-synaptic connections from S1 to V1, via parietal-cortical regions (Barbour & Callaway, 2008; Beck, Pospichal, & Kaas, 1996; Karlen & Krubitzer, 2007). This type of study also reveals that neurons in the primary sensory cortex tend to respond to one type of sensory stimulation, yet responses to multi-modal input have been demonstrated (Campi, Bales, Grunewald, & Krubitzer, 2010). Besides the cortico-cortical projections between somatosensory and visual areas, somatosensory caudal areas have been shown to participate in multi-modal processing, as well as it happens in posterior parietal areas (Anomal, Rocha-Rego, & Franca, 2011). The majority of these studies also emphasize the key role of thalamus and thalamo-cortical connections.

Event related potentials (ERPs) allow examination of the processing resources allocated to

stimulus evaluation during different stages of information processing (Hillyard & Kutas, 1983) and could thus be an ideal technique to analyze cortical plasticity along time (Eldar & Bar-Haim, 2010), specifically for bottom-up cerebral activity measured by early evoked potentials, like P50 and N100 components. Around 50 msec, and even earlier, primary somatosensory cortical activation is normally found. Circa 100 msec, shape and object automatic recognition takes place, also in somatosensory areas (Lucan, Foxe, Gomez-Ramirez, Sathian, & Molholm, 2010).

Transcranial magnetic stimulation (TMS) can induce activity in stimulated cortical neuronal networks in a non-invasive manner (Hallett, 2007). By delivering repetitive TMS (rTMS) it is possible to induce changes in brain excitability that outlast the stimulation period (Pascual-Leone, et al., 1995). These induced changes in cortical excitability are a form of neural plasticity. The after-effects of rTMS might relate to activity-dependent changes in the effectiveness of synaptic connections (Di Lazzaro et al., 2010; Hallett, 2007).

We analyzed brain changes during and after an extended repetitive passive tactile training in a single left handed blind individual to determine if cortical areas were recruited during the longitudinal long-term training process and after its cessation. Then, we assessed if occipital “colonization” was paramount for object recognition by applying inhibitory rTMS on the occipital areas affecting the performance in object recognition.

## CASE REPORT

A 50 year old male volunteer, left-handed, with over 97% loss of vision from the age of 3 onwards, who suffers from Peter’s anomaly (a rare, congenital anomaly of the anterior segment of the eye characterized by a central corneal opacity, usually accompanied by the adhesion of strands of iris tissue to the margins of the opacity, thinning of the stroma and attenuation or absence of Descemet’s membrane, and normally accompanied by other ocular malformations) and microphthalmia, who enjoys nowadays only light vision and finger-counting at less than 5 cms, was stimulated on his left hand with repetitive passive tactile stimulation.

The stimulation program was completed over a period of 3½ months and involved daily sessions five days a week. Each stimulation session lasted 60 minutes (1 stimulus/sec, 3600 stimuli/session).

The program consisted in repetitive tactile stimulation on his palm with lines oriented vertically, horizontally or obliquely using a tactile piezoelectric device. Each line was presented for 300 msec at 40 Hz, one line every second. The frequency of 40 Hz was chosen based upon the findings that thalamo-cortical connections fire at 40 Hz (Llinas & Ribary, 1998). The line presentation was ensued by a blank pause of 700 msec.

## METHOD

### Technique

The generation of repetitive passive tactile stimuli was achieved using a single tactile piezoelectric device (a tactile matrix with  $32 \times 48$  pixels). Each nylon point had a 1.3 mm diameter and they were spaced every 2.4 mm, equally in both dimensions. The device generated a 5 cms double line made up of 30 dots each (60 dots in total). The dots of each line were stimulated simultaneously, not directionally.

EEG was recorded with a 32 channel Neuronix Medicid<sup>®</sup> Equipment using a standard 10–20 electrocap. Impedance of all electrodes was kept below 5k $\Omega$ . The electrooculogram (EOG) was recorded with two pairs of leads in order to register horizontal and vertical eye movement. Data were recorded using a mastoid electrode as reference. Sampling rate was 1000Hz. Amplifier frequency bands were set between 0.05–30.0 Hz.

### Source localization

Low-resolution electromagnetic tomography (LORETA) (Pascual-Marqui, Michel, & Lehmann, 1994) was applied to this individual ERP recording to identify underlying brain electric sources of the scalp potentials. LORETA is a reverse solution method that computes the three-dimensional distribution of neural generators in the brain as a current density value (A/m<sup>2</sup>) for a total of 2394 voxels, with the constraint that neighbouring voxels show maximal similarity. This analysis was realized for a time window between 20 and 70 msec (between –10 and +10 msec starting from the high amplitude peak measured from the Pz electrode).

Brain volume anatomical restrictions were applied for cerebral electrical tomography (CET) calculations and an average brain template was used. CET data were analyzed in the time domain

and tomography was calculated for each instance separately. Two source analyses models were defined by constraining the source to one anatomic compartment, chosen using the probabilistic brain atlas (PBA) (Collins, Neelin, Peters, & Evans, 1994; Mazziotta, Toga, Evans, Fox, & Lancaster, 1995) and Brodmann atlas.

### Behavioural and EEG measurements

The subject was instructed to simply experience the stimulation and try to identify the line orientation without moving his hand. For the behavioural assessment, the blind volunteer was asked to discriminate pairs of tactile stimuli: horizontal (80% of the stimuli, frequent) or oblique lines (20%, infrequent) by pressing a button whenever an oblique line was detected. Subject's responses, errors and response times were collected for further analysis.

For the ERP study, EEG recording was performed in a soundproof room and with dim lighting. The blind volunteer was comfortably seated and was instructed to stay awake and avoid abrupt movements. Only non-target trials (horizontal lines) were considered for P50 and N100 analysis in order to avoid contamination with motor neural activation during response production. The purpose of using only the frequent stimuli/oddball paradigm was to separate attentional and motor components in the potential. Epochs were 1000 msec in duration with a 200 msec pre-stimulus interval and a post-stimulus length of 800 msec. Baseline was defined as the average voltage over the period from 200 msec prior to stimulus onset.

In order to control for eye movements, our volunteer was required to keep his eyes closed throughout the experiment. In this way it was not feasible to directly observe blinking or eye movements but we monitored both eye movement and blinking artifacts through continuous and simultaneous EOG (with EEG). Those evoked potentials that were contaminated with eye movements were excluded from final analysis.

### Chronogram

Seven evaluations were conducted: baseline, at the beginning of the experiment (prior to any stimulation), E1 at the end of the first week of the beginning of tactile stimulation, E2 after two weeks

of the second evaluation, E3 after four weeks of the third evaluation, E4 after eight weeks of the fourth evaluation, E5 after one month without tactile stimulation and E6 after three months without tactile stimulation.

## rTMS

rTMS was performed using a Magstim 2 stimulator which delivers a theta burst inhibitory protocol (Huang, Edwards, Rounis, Bhatia, & Rothwell, 2005). During the rTMS our blind volunteer was requested to perform line orientation tasks. rTMS during 22 sec of 3 pulse theta bursts of 40 Hz, with 60% power, simultaneous with tactile stimulation, were given at calcarine cissure and, posteriorly, 5 cm above the inion. During the rTMS our blind volunteer was requested to perform line orientation tasks.

## RESULTS

The behavioural results showed an increase in discriminative ability (% of tactile stimuli correctly identified) as repetitive tactile stimulation progressed during the first 3½ months. It was sustained for the following three months, when tactile stimulation had ceased. Improvement in discriminative ability was accompanied by a shortening in reaction time (Table 1). A gross 15% decrease in RT was observed. Both the percentage of correct identifications and RT remained fairly constant during the three months consecutive to training cessation. All behavioural data (RT, % of errors) and ERP ones are provided in Table 1.

After about 60 sessions of hourly passive tactile stimulation the subject described a change in the quality of stimuli perception. This can be better

illustrated by his open-account narrative: “[a] major change happened when, suddenly, I completely forgot the tactile sensations and started seeing in my mind the images transmitted by the tactile stimulator . . . It is as if I could see a luminous line on the dark screen.” At the end of tactile stimulation (from weeks 7 to 15) there was also a marked increase in occipital activity (E4) concomitant with the visual sensations previously described by the subject.

EEG results are detailed in Table 2. Maximally activated areas were found initially in temporo-parietal areas and towards the end of the experiment they were mostly occipital, a fact which remained three months after training cessation. An occipital lobe analysis was carried out *a posteriori* to refine the analysis of the most activated areas at the end of the experiment. It showed a progressively increasing occipital activity in both lingual and calcarine areas along the passive tactile training. This occipital activity remained stable after the cessation of tactile training (Figure 1).

EEG recording during tactile stimulation during the baseline session, that is to say, during the first 3600 stimuli, was carried out. No detectable occipital activation occurred at that time.

On the other hand, our volunteer was required to perform visual imagery tasks of lines in different orientations. He was requested to think about arrows pointing in different directions. This activity failed to show any relevant occipital activity.

When theta burst rTMS trains, which provoke an over a minute suppression of neuronal activity, were applied over the calcarine sulcus, the subject lost 18% accuracy in line orientation. In other words, an 18% reduction in accuracy or, equally, a correct response rate of 82% after TMS is applied over the occipital area. However, when the same rTMS was applied over an area 5 cm above the inion, the

TABLE 1

Behavioural and ERP data. Baseline: at the beginning of the experiment. E1: end of the first week after commencement of tactile stimulation. E2: two weeks after E1. E3: four weeks after E2. E4: eight weeks after E3. E5: one month without tactile stimulation. E6: three months without tactile stimulation

	Baseline	E1	E2	E3	E4	E5	E6
Reaction Time (ms)	750	678	687	684	651	660	657
% Correct Responses	70%	93%	95%	96%	95%	94	92
% Errors	30%	7%	5%	4%	5%	6%	8%
Pz Latency	92	128	117	106	80	108	115
Oz Latency	93	130	118	108	82	105	109
Pz Amplitude	-1.74	-0.10	-0.24	-0.48	-0.07	-0.08	-0.04
Oz Amplitude	-1.58	-0.40	-0.48	-0.62	-0.37	-0.14	-0.10

**TABLE 2**

Main neuroanatomical structures according to projection areas of maximal intensity in P50. AAL: Anatomical label corresponding to Probabilistic Brain Atlas. BA: Brodmann areas. x, y, z: co-ordinates from PBA in three spatial axes

<i>Cortical areas involved (PBA)</i>	<i>BA</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>Voxels %</i>
<b>Baseline</b>					
Right superior temporal	48	36	68	96	100,0000
Right superior temporal	38	37	68	91	95,5818
Right superior temporal	22	38	66	93	94,8007
Right middle temporal	21	39	63	92	90,3819
<b>Evaluation 1</b>					
Left calcarine	17	92	80	172	100,000
Left lingual	17	92	77	172	99,8499
Right calcarine	17	87	80	169	97,8103
Right lingual	17	87	75	170	93,5516
Left superior temporal	42	148	88	125	91,0530
Left middle temporal	22	148	84	138	92,8862
Left middle temporal	21	148	81	140	92,0725
Left superior temporal	22	148	76	112	89,3515
Left superior temporal	48	147	71	104	84,9763
Left cuneus	18	92	95	160	85,3452
Right precuneus	7	88	94	158	85,2102
Right cuneus	18	86	93	162	84,3202
Left middle temporal	37	143	77	148	85,8641
<b>Evaluation 2</b>					
Left temporal superior	22	148	76	108	100,0000
Left temporal superior	48	147	72	100	97,1365
Left superior temporal	42	149	80	120	75,8628
Left cuneus	18	88	98	159	93,7111
Right precuneus	7	88	100	159	93,6145
Left middle temporal	21	148	71	113	92,6605
Left calcarine	17	92	87	163	89,7373
Right calcarine	17	87	89	160	89,1330
Right superior temporal	22	32	71	104	89,1243
Right superior temporal	48	32	71	103	88,3108
Right cuneus	18	85	95	161	86,5292
Left middle temporal	22	148	81	134	85,3380
Left inferior parietal	3	140	118	117	79,4052
Right superior temporal	21	140	62	93	79,4052
<b>Evaluation 3</b>					
Left calcarine	17	92	76	176	100,0000
Left middle temporal	37	145	69	148	93,0666
Right calcarine	17	85	73	175	92,0554
Left middle temporal	21	148	76	140	91,0400
Left inferior temporal	37	145	65	153	82,5845
Left superior temporal	22	148	78	140	90,6233
Right lingual	17	85	69	176	88,8780
Left superior temporal	42	148	85	131	86,1428
Left lingual	17	99	69	174	84,6058
<b>Evaluation 4</b>					
Left calcarine	17	88	80	172	100,0000
Left lingual	17	88	75	172	97,1537
Right calcarine	17	87	88	164	96,0134
Right cuneus	18	87	92	160	95,6036
Left cuneus	18	92	96	160	95,8859
Right precuneus	7	88	102	159	94,7376
Right lingual	17	87	75	169	92,0106
Left precuneus	7	92	103	157	93,5003

(Continued)

**TABLE 2. Continued.**

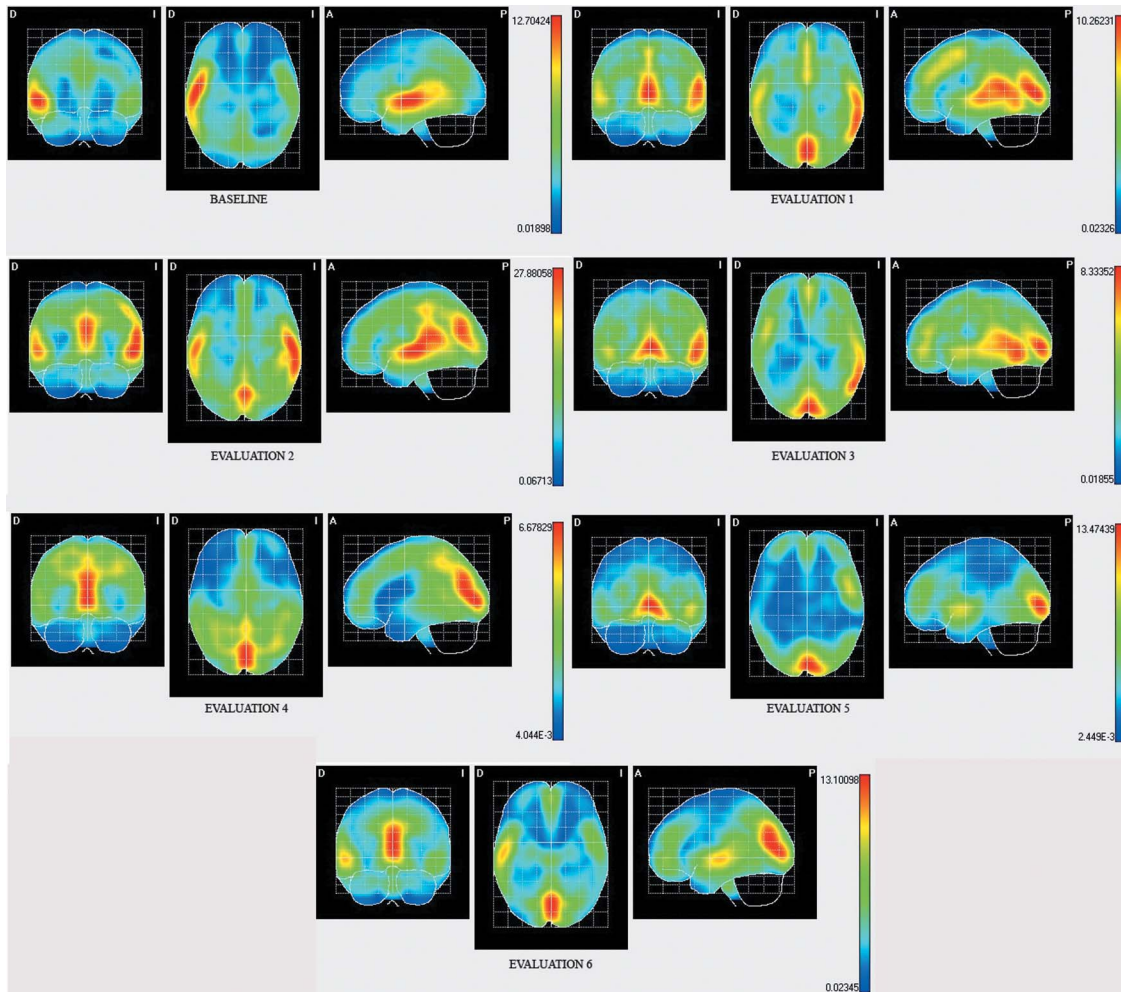
<i>Cortical areas involved (PBA)</i>	<i>BA</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>Voxels %</i>
<b>Evaluation 5</b>					
Left calcarine	17	92	74	176	100,000
Right calcarine	17	85	72	177	95,4337
Left lingual	18	97	68	174	88,1879
Right lingual	17	85	69	177	87,0880
<b>Evaluation 6</b>					
Left calcarine	17	92	88	164	100,000
Left cuneus	18	92	92	164	98,7085
Right calcarine	17	88	89	163	98,5364
Right precuneus	7	88	99	159	96,2696
Right cuneus	18	87	96	161	95,3265
Left precuneus	7	92	99	157	95,1610
Left lingual	17	92	74	172	91,1087
Right lingual	17	87	75	170	87,8186

subject was 100% accurate (Figure 2). rTMS over the calcarine sulcus also brought a reduction in the subjective perception of “seeing,” as described by our subject: “[d]uring that time I did not experience the same sensation of lights over a blackboard corresponding to the lines on the stimulator . . . I could not perceive well at all . . . .”

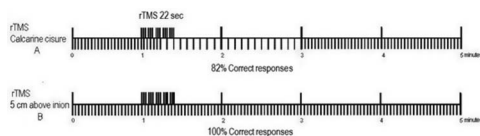
**DISCUSSION**

The single most striking finding of this case is that occurrence of visual-like perception (visual qualia) is correlated with the development of evoked EEG activity in occipital areas; furthermore, inhibition of cortical activity with inhibitory rTMS transiently prevented both the occurrence of object orientation and recognition and the occurrence of visual “qualia” in this patient. Thus, a causal connection can be suggested between remapping of somatosensory input to occipital cortex and the development of visual-like perceptions associated with object recognition through passive tactile stimulation. A functional role for visual cortex activation through active tactile stimulation has been hypothesized by Cohen et al. (1997) who showed, using rTMS, that the occipital area is required for Braille reading in blind subjects.

Our subject spontaneously reported “seeing” the orientation of tactile lines after about 200,000 stimulations and his report was simultaneous with the occurrence of a predominant occipital cortical activity. Most importantly, upon occipital inhibition with rTMS he experienced reduced subjective perception of sight as well as an objective



**Figure 1.** Maps source analysis (LORETA) obtained in P50. Energy projection activity progression in calcarine and lingual cortical areas. Left calcarine in baseline (44.52%), E1 (100%), E2 (89.74%), E3 (100%), E4 (100%), E5 (100%), and E6 (100%). Right calcarine in baseline (41.85%), E1 (97.81%), E2 (89.13%), E3 (92.06%), E4 (96.01%), E5 (91.4337%), and E6 (98.54%). Left lingual in baseline (27.83%), E1 (99.85%), E2 (79.79%), E3 (84.61%), E4 (97.15%), E5 (88.19%), and E6 (91.11%). Right lingual in baseline (26.54%), E1 (93.55%), E2 (71.91%), E3 (88.88%), E4 (92.01%), E5 (87.09%), and E6 (87.82%). To view this figure in color, please see the online version of this article.



**Figure 2.** Repetitive transcranial magnetic stimulation (rTMS) and tactile stimulation. A: rTMS during 22 sec of 3 pulse bursts of 40 Hz simultaneous with tactile stimulation at calcarinecisure the subject did not respond correctly to 18% of tactile stimuli at the end of the magnetic stimulation and during 2 minutes (82% of correct answers). B: rTMS during 22 sec at 5cm above inion during tactile stimulation the visual tactile responses were all correct during and after rTMS.

loss of behavioural performance on a recognition task. This observation strongly suggests that, in this individual, perceptual processing of the

somatosensory information for the recognition task was dependent on evoked activation of the occipital cortex (Gizewski et al., 2003).

The observation of reduction in RT in our case might be interpreted as an instance of strengthened synaptic connections in a newly established network. Some consider that neuronal plasticity can only be accomplished through reinforcement of pre-existing connections (Pascual-Leone et al., 2005).

While functional activation of the visual cortex by non-visual stimulation in blind subjects has already been shown after brief periods of tactile stimulation, its persistence has been studied for lesser periods than in our study (Amedi, Raz, Azulay, Malach, & Zohary, 2010; Lepore et al., 2010). Diachronically, in our experiment, persistent



activity appears more in temporo-occipital areas (ventral pathway) than parieto-occipital (dorsal pathway) ones (Amedi et al., 2010; Kandel & Wurtz, 2000), except at the end of the training period, when they are re-routed towards occipital areas. Different roles have been proposed for the ventral pathway (or inferior temporal one) and the dorsal (or parieto-occipital) one. The former deals with shape and form information derived from the edges and borders, therefore its neurons are sensitive to images outlines, their orientation and their boundaries. The ventral pathway system is considered to be capable of high resolution which, in turn, allows seeing stationary objects in detail. The dorsal pathway deals mostly with motion and depth. In our case the nature of the information is not strictly spatial, but lines with different orientations and our findings support previously available literature (Kandel & Wurtz, 2000) as we found more activation in temporal than in parietal areas until the fourth evaluation (Table 1). From then onwards the main activity happened in occipital areas.

The persistence of occipital activation in our subject may be linked to the lack of any other subsequent competing stimuli, such as an auditory one, providing spatial information. In animals, a potentiated response, although lasting hours–months, can be actively eliminated (or depotentiated) with the application of low-frequency electrical stimulation, and such changes might be involved in the homeostatic regulation of plasticity to prevent saturation, to facilitate extinction and forgetting and to improve signal information processing by enhancing neuronal signal-to-noise ratios. On the other hand, some experiments have shown that non-invasive rapidly presented sensory stimuli can induce Long-Term Potentiation (LTP) in specific regions of sensory cortex in healthy humans (Clapp, Hamm, Kirk, & Teyler, 2011), but the longevity of this response has not been established. Moreover, human cortical LTP can be induced by naturalistic visual experience, arguing that it is a normal constituent of visual information processing in the brain (Cooke & Bear, 2010). Yet, the functional role of LTP in human subjects has not been studied so far.

One of the most intriguing and pressing questions is what happens in congenitally blind people when they undergo tactile training. Putting aside the fact it would be difficult to phenomenologically describe the qualia of vision for those who have never had any previous experience of seeing,

our group has failed to see any occipital cortex activation with prolonged passive tactile training in a small group of four people with blindness from birth (Ortiz et al., 2011). Other authors (Lewis, Saenz, & Fine, 2010; Matteau, Kupers, Ricciardi, Pietrini, & Ptito, 2010), using very small samples as well, found visual cortex activation, though they used fMRI. Because of the different temporal resolution between EEG and fMRI this discrepancy is also difficult to explain as fMRI findings are more complex to interpret. So far, the results are contradictory and this is clearly a gap in scientific literature that needs to be addressed with larger studies. Our subject was not congenitally blind and all subjects who had undergone a similar passive tactile training who experienced visual qualia concomitant with occipital cortex activation were not congenitally blind (Ortiz et al., 2011).

One aspect in which research with congenitally blind people could help enormously is in extricating the component visual imagery might have. Early sensory cortex is activated during visual imagery, as fMRI studies have shown, though damage to early visual cortex does not preclude visual imagery (Kosslyn, Ganis, & Thompson, 2001). However the hypothesis that visual imagery might have played a role in our subject is most unlikely if we take into account the following issues.

Engagement of visual imagery would have been linked with occipital cortex activation from early moments (Kosslyn et al., 2001), yet in our case the activation of the occipital cortex did not occur until 200,000 stimuli had been administered. Visual imagery as such did not result in occipital activation in our subject; we asked our volunteer to think about arrows pointing in different directions and no important occipital activity was elicited. We did record EEG during tactile stimulation on the baseline session, that is to say, during the first 3600 stimuli, and no detectable occipital activation occurred at that time.

Visual imagery tends to be reflected in evoked potentials after 200 msec (Tadi, Overney, & Blanke, 2009). Hence potential visual imagery impact upon our results is discarded by analyzing very early phenomena, specifically P50. Activation of occipital cortex 50 ms after the tactile stimulus is too fast to be driven by imagery. Moreover, any imagery strategy used to interpret a somatosensory image would take longer than 200 msec or, if anticipatory, would have resulted in a readiness potential (such as contingent negative variation, CNV). We did not observe CNV in our data.

There is also a solid body of research revealing that imagery, when engaged, is involved from the beginning of a task, and often shows greater involvement early and becomes progressively less with time (Decety, Jeannerod, & Prablanc, 1989; Decety & Lindgren, 1991). Our findings are exactly the more the training progresses, the more occipital activity, yet this activity failed to exist at the beginning. Occipital activation increases over time, in correlation with increased task proficiency. Visual imagery exercises did not elicit much occipital activity in the case of our subject. This adds weight to rule out visual imagery as a major cause of occipital activation in our volunteer.

Finally, there are also criticisms to the hypothesis that visual imagery can be responsible for important occipital activation (Amedi, Jacobson, Hendler, Malach, & Zohary, 2002; Amedi, Malach, Hendler, Peled, & Zohary, 2001; Kosslyn et al., 2001; Kosslyn, Thompson, & Sukel, 2005). Visual imagery is not an obligatory condition for object activation in the visual cortex (Amedi et al., 2010).

Besides visual imagery, the role of practice effects, versus new skill acquisition, is a difficult one to weight and deserves some consideration. Undeniably, repeated practice was a crucial factor in promoting the observed brain changes in our volunteer. However, regardless of the role of practice, the crucial novel finding, is that with repeated practice the neural substrate for the task changes and the occipital cortex becomes engaged in the task. In fact, the TMS experiment reveals that the occipital cortex activation plays a causal role in eventual task performance. So, putting aside the specific role of practice, the 'visual cortex' becomes causally involved in tactile processing over time. That shows a change in brain substrate for task performance that would not be expected without the hypothesis of cross-modal plasticity.

If performance improvement had to be explained exclusively on the basis of practice on a tactile task, there would be no explanation for the deterioration experienced by magnetic stimulation of the occipital cortex. There is also some indirect evidence in previously available literature that improvement in visual areas may not be attributed to practice (Andersen et al., 2010). We cannot but conclude that our explanation (of cross-modal acquisition) is the most parsimonious and indeed the most logical account for the effect of TMS.

We agree with Poirier et al. (2007), that cross-modality is an early predominant process in the blind during the first tactile stimulations but,

with training, sensory substitution mainly induces recruitment of occipital areas. Some authors have shown occipital activation in blind subjects when they carry out auditory localization under monoaural conditions, a task they perform better than sighted people (Gougoux et al., 2005). A possible explanation consistent with our results is that, at the beginning of tactile stimulation, blind people activate many other neuronal circuits different than sighted people to compensate for their visual loss but, after passive repetitive tactile training, their brain is re-organized towards areas more efficient in tactile-spatial processing (Ortiz et al., 2011). We mentioned in the introduction the demonstrated connectivity between A1 to V1 and the existence of multi-synaptic connections from S1 to V1, via parietal-cortical regions, in animal studies. Some of these areas and neurons are capable of multi-modal response. These may be presumably the substrate for our demonstrated effects.

In short, this case proves that extended passive tactile stimulation leads to an increased and sustained neuronal plasticity towards visual cortical areas (Lucan et al., 2010), which can elicit a subjective vision-like experience in a blind subject. Moreover, this occipital activity appears to be a key factor in blind subjects for object orientation. Based on the previous findings we propose the existence of specific brain networks for processing spatial information which are independent of the sensory modality input. We hypothesize that the visual cortex somehow "competes" for the preferential processing of this spatial information in people with blindness.

Single-case studies possess intrinsic limitations. With regards to the effect of TMS upon visual cortex the question remains if performance disruption in the same task in healthy individuals without any extensive training would yield a similar effect. In effect, it might be argued that if the same reduction in accuracy was observed in healthy individuals without extensive training, then the TMS data would need further reviewing. This is a research issue which needs to be addressed in the future.

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