A Computational Neuroscience Account of Visual Neglect

Dietmar Heinke [a] Gustavo Deco [b] Josef Zihl [c]
Glyn W. Humphreys [a]

[a] *Behavioural and Brain Sciences Centre, School of Psychology, University of Birmingham, Birmingham B15 2TT, United Kingdom*
d.g.heinke@bham.ac.uk

[b] *Siemens AG, Corporate Technology, Computational Neuroscience, CT IC 4 Otto-Hahn-Ring 6, 81739 Munich, Germany*

[c] *Institute of Psychology, Neuropsychology Ludwig-Maximilians-Universität München. Leopoldstr. 13, 80802 Munich, Germany*

Abstract

On the basis of a computational and neurodynamical model, we investigate a cognitive impairment in stroke patients termed visual neglect. The model is based on the "biased competition hypothesis" and is structured in several network modules which are related to the dorsal and ventral pathway in the visual cortex. By damaging the model, visual neglect can be simulated and explained as an unbalanced neurodynamical competition. We predict that acquiring knowledge of objects can increase the frequency of saccades to previously ignored object parts. This prediction is confirmed in a single case study by monitoring eye movements of a neglect patient.

Key words: Computational Neuroscience, Visual Neglect, Prediction, Single Case Study, Eye Movements

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1 Introduction

In neurological patients, visual deficiencies can result from damage to different brain regions. Particularly, unilateral parietal damage, could lead to symptoms of the neglect syndrome, wherein patients fail to notice the existence of objects or events in the hemispace opposite their lesion site (e.g. [2]). Despite the ardent interest in the neglect syndrome, the underlying causes leading to

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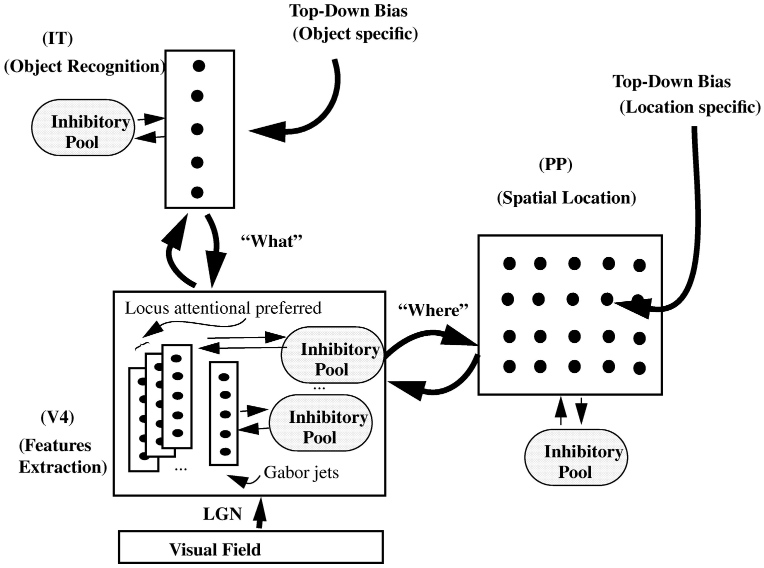

Fig. 1. Cortical architecture for visual attention.

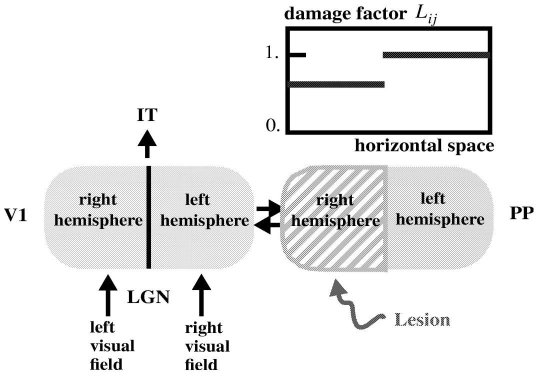

Fig. 2. Lesioning of the PP complex.

this disorder are still obscure and an issue of controversy. A systemic explanation of the neuropsychological findings on visual neglect would lead to a better understanding of the mechanisms underlying the representation of visual space and the control of visual attention. Here, we analyze the relation between visual neglect and the underlying neural basis of visual attention in the framework of a computational model. We go on to experimentally test a prediction of the model.

2 Computational Model

Fig. 1 depicts the model of visual attention for object recognition and visual search which is based on the biased competition hypothesis [4]. [1] gives the mathematical details for the model. The model is essentially composed of three modules structured such that they resemble the two known main visual

Fig. 3. The 3 images illustrate locations of activations in the PP (dots) together with the input image. They contrast the response of the model without being lesioned (left), with being lesioned but excluding top-down influence (middle) and, finally, including top-down influence in the lesioned condition (right).

paths of the visual cortex. Information from the retino-geniculo-striate pathway enters the visual cortex through area V1 in the occipital lobe and proceeds into two processing streams. The occipital-temporal stream (”what” pathway) leads through V2, V4 and IT (inferotemporal cortex) and is mainly concerned with object recognition. The occipito-parietal stream (”where” pathway) leads into PP (posterior parietal complex) and is concerned with the location and spatial relationships between objects. The first module (V4) of our system is engaged in the extraction of features and consists of pools of neurons with Gabor receptive fields tuned to different positions in the visual field, orientations and spatial frequency resolutions. The ”where” pathway is given through the mutual connection with the second (PP) module that consists of pools codifying the position of the stimuli. The connections with the first module originate from a top-down bias on attention associated with the location of the stimuli. Finally the third module (IT) of our system is engaged with the recognition of objects and consists of pools of neurons which are sensitive to the presence of a specific object in the visual field. The pools in IT are synaptically connected with translationally invariant receptive fields with pools of the first module (V4), such that, based on the Gabor features, specific objects are invariantly recognized. The mutual connections between IT and V4 modules represent a top-down biasing of attention associated with specific objects. The model operates in two different modes: the learning mode and the recognition mode. During the learning mode the synaptic connection between V4 and IT are trained by means of Hebbian learning during several presentations of specific objects at random positions in the visual field. During the recognition mode there are two possibilities of running the system. First, the model can be biased towards a certain location by using top-down modulation in the PP module (see [3] for details). Second, an object can be localized in a scene (visual search) by biasing the system with an external top-down component at the IT module. The IT module is driven in favor of the pool associated

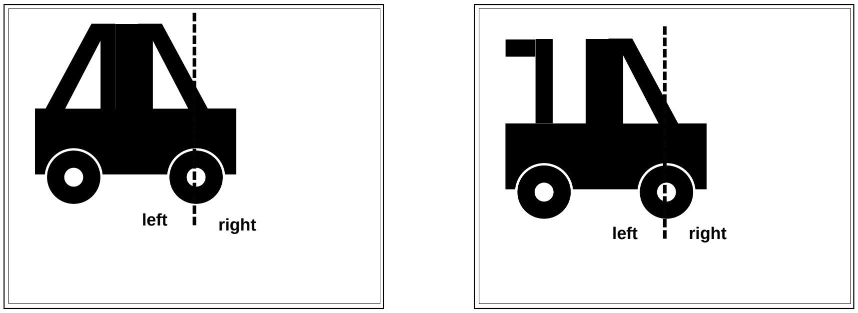

Fig. 4. Illustration of 2 objects. For analyzing the results, the location of fixations in objects were categorized into two different areas (right, left) with respect to the screen.

with the specific object. In turn, this enhances the activity of the pools in V4 associated with the features of the specific object leading to a search for the specified object. In addition, the intermodular modulation V4-PP drives the competition in favor of the pool localizing the specific object. Both forms of external top-down bias are assumed to come from frontal areas of the cortex that are not explicitly modeled. In addition, we assume that the PP module drives eye movements during the perception of objects, so that highly activated spatial locations in the PP module correspond to regions attracting fixations. To visualize the results, locations in the PP module whose activation passes a threshold in the final state are marked with dots in the input image (see Fig. 3). These dots indicate possible locations for eye fixations.

3 Simulation of Visual Spatial Neglect

The model was trained with an image from the Carnegie Mellon Database (see Fig. 3). Because visual neglect usually follows a lesion to the parietal cortex, the corresponding structure in the model, the PP module, was lesioned in a stepwise fashion (see Fig. 2). The lesion was applied in an intrinsic way, damaging only connections within the module (see [3] for details). The behaviour of the model was analyzed in two conditions: 1) no top-down knowledge is used; 2) top-down object specific knowledge is used. The first condition is simulated by cancelling the external top-down bias impinging on IT (see Fig. 3 middle). This simulation result matches the abnormal scan path typically observed in visual neglect [5]. The second condition is simulated by reinforcing positively with an external positive top-down bias the IT pool associated with the recognition of the specific face. As a consequence, the PP module shows an increased activation on the left side of the object compared to the result with no top-down influence (Fig. 3 right). This results from the fact that the pool activity in the damaged PP hemisphere is reinforced by the stronger activity in the corresponding right hemisphere in the V1 module which are strongly stimulated by the feedbacks coming from the positively top-down reinforced

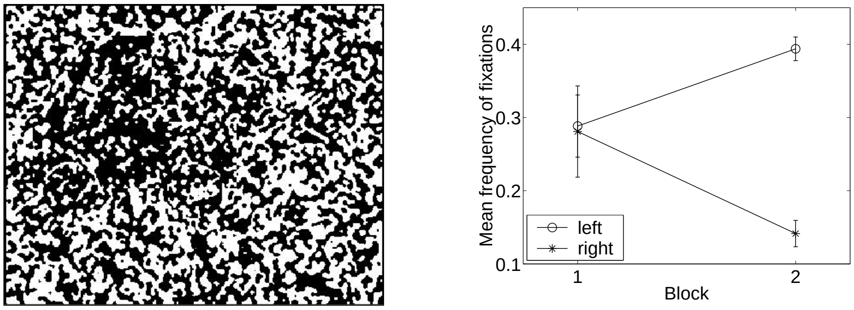

Fig. 5. Example of the stimuli ”car” on the left. Note that this picture might not reflect the difficulty of the display used in the study, because the recognition of the object strongly depends on the exact size of the image. The graph on the right shows how the emphasis of fixations shifts from the right to the left of objects and screen.

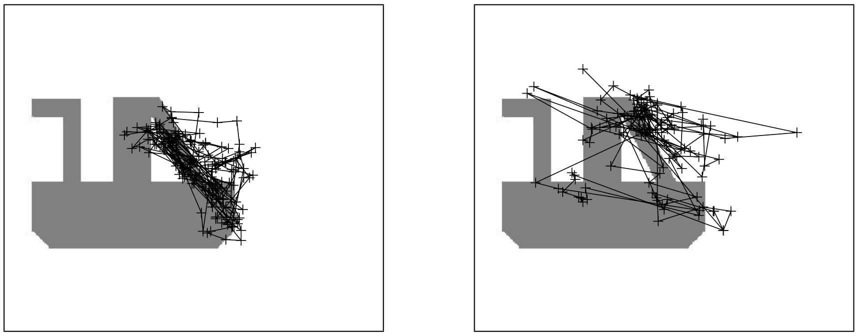

Fig. 6. Example of alteration of scan path (left before learning and right after learning)

IT pool. Since the PP module is assumed to drive saccades, the simulation result predicts an increased number of fixations on the left side of objects as a consequence of improved object knowledge. In the following section this prediction was tested.

4 Experimental Results: Top-down Effect on Saccadic Patterns

We analyzed the influence of object knowledge on the saccadic patterns in a patient (MB) with mild left neglect by using four objects: ”car”, ”lorry”, ”ship” and ”cargo ship” (see Fig. 4). Each object appeared at two vertically different locations in the images keeping the axis, marked with a broken line in Fig. 4, always aligned with the centre of the screen. Noise was applied to each image (see Fig. 5). The chosen level of noise made it difficult for MB to recognize the objects without any additional information. The images were presented to MB twice in two separate blocks. In the first block MB had no knowledge about the objects and she was asked to guess what object could be hidden. Before the second block, the objects were shown to MB without noise. Subsequently, MB correctly report 10 out of 16 objects in the second block, while having recognized none of them in the first block. Also, MB's eye movement altered from block one to block two (see Fig. 6 for an example). To analyze the eye movements quantitatively, the area of the four objects was divided into "right" and "left" (see Fig. 5). The average frequency of fixations for the areas was computed. An ANOVA showed that the factor block had a significant influence on the frequency of fixations on the left side ($F(1,47) = 6.56, p < 0.05$) and on the right side ($F(1,47) = 4.37, p < 0.05$). In fact, Fig. 5 shows that the frequency of fixations on the left side was increased, confirming the prediction of the model.

5 Conclusion

This paper presented a computational and neurodynamical model of visual attention based on the "biased competition hypothesis". The posterior parietal complex of the model was lesioned so that the competition in its neural pool favored the right side over the left side of the scene and object. Consequently, the model exhibited eye movements similar to visual neglect patients. Hence, the model explains visual neglect and the related fixation pattern as a result of an imbalanced competition between the left hemisphere and the right hemisphere. In addition top-down influence in the model can amend the eye movements shifting their focus more to the left side. This prediction was confirmed in a single case study, adding further support for the validity of the model. The model explains this experimental finding by the fact that the competitive imbalance in the posterior parietal complex can be alleviated via top-down influence from the IT via V1 and V4.

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