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Deficit in feature-based attention following a left thalamic lesion

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ABSTRACT

Selective attention enables us to prioritise the processing of relevant over irrelevant information. The model of priority maps with stored attention weights provides a conceptual framework that accounts for the visual prioritisation mechanism of selective attention. According to this model, high attention weights can be assigned to spatial locations, features, or objects. Converging evidence from neuroimaging and neuropsychological studies propose the involvement of thalamic and frontoparietal areas in selective attention. However, it is unclear whether the thalamus is critically involved in generating different types of modulatory signals for attentional selection. The aim of the current study was to investigate feature- and spatial-based selection in stroke survivors with subcortical thalamic and non-thalamic lesions. A single case with a left-hemispheric lesion extending into the thalamus, five cases with right-hemispheric lesions sparing the thalamus and 34 healthy, age-matched controls participated in the study. Participants performed a go/no-go task on task-relevant stimuli, while ignoring simultaneously presented task-irrelevant stimuli. Stimulus relevance was determined by colour or spatial location. The thalamic lesion case was specifically impaired in feature-based selection but not in spatial-based selection, whereas performance of non-thalamic lesion patients was similar to controls' performance in both types of selective attention. In summary, our thalamic lesion case showed difficulties in computing differential attention weights based on features, but not based on spatial locations. The results suggest that different modulatory signals are generated mediating attentional selection for features versus space in the thalamus.

1. Introduction

Selective attention is an effective mechanism to cope with the daily flood of sensory information that reaches our senses and typically exceeds the limited processing capacity of our brain. Attention can be directed to spatial locations (Posner, 1980; Posner et al., 1982; Treisman and Gelade, 1980), features such as an object's colour or shape (Baylis et al., 1993; Driver and Baylis, 1989; Harms and Bundesen, 1983; Kramer and Jacobson, 1991; Maunsell and Treue, 2006) as well as whole objects (Duncan, 1984; Egly et al., 1994; Kanwisher and Driver, 1992; Vecera and Farah, 1994). Spatial-, feature- and object-based perceptual representations are weighted depending on the expectations and internal goals of the observer and integrated with information about the perceptual properties of the stimuli (e.g. the physical salience). The computed attention weights can be topographically represented in a priority map reflecting which elements will be preferentially processed (Bisley and Goldberg, 2010; Bundesen et al., 2005; Desimone and Duncan, 1995; Liu et al., 2011).

The concept of priority maps for attentional selection dates back to the concept of saliency maps, which has been introduced by Itti, Koch and colleagues (Itti and Koch, 2001; Koch and Ullman, 1985; Baluch and Itti, 2011). These authors described a computational model of 'bottom-up' selection. According to this model, visual input is first filtered by different feature-detection subsystems to create feature maps, e.g. for orientation, luminance and colour. Neural activation in each feature map represents the salience of that feature across the visual field. These feature maps are combined into a single saliency map, whose "peak" determines attentional selection of the target object based on a winner-take-all mechanism (Bisley and Goldberg, 2010; Bundesen et al., 2011). Importantly, in this model, 'saliency maps' are computed in a purely bottom-up manner. We use the term 'priority map' to emphasise bottom-up and top-down influences on attentional selection.

Converging evidence from functional neuroimaging and lesion-based studies indicate that modulatory signals mediating attentional selection are generated by a large-scale network of regions in the frontoparietal cortex and the thalamus (for recent reviews, see Ptak, 2012; Scolari et al., 2015; Vandenberghe and Gillebert, 2015; Vandenberghe et al., 2012). Functional neuroimaging studies in healthy volunteers show overlapping activations during spatial-, feature- and

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object-based attention within the frontoparietal network (e.g., Bressler et al., 2008; Egner et al., 2008; Ester et al., 2016; Fink et al., 1997; Giesbrecht et al., 2003; Hou and Liu, 2012; Liu, 2003; Peelen and Mruczek, 2008; Scolari et al., 2015). For instance, Giesbrecht et al. (2003) found that both colour and location cuing were associated with activity in the superior frontal and posterior parietal cortex. However, besides the common, domain-independent control network, distinct subpopulations of neurons are associated with feature- and spatial-based attention and even with attention to different features (Liu et al., 2011). In particular, neurons in the prefrontal cortex appear to be the source of feature-based attention (Bichot et al., 2015) (Baldauf and Desimone, 2014). Other components of the frontoparietal network are specialised for spatial-based attention, such as the right inferior parietal lobule, which appears to be more responsive to spatial cues than to colour cues (Vandenberghe et al., 2001b). Thus, different regions within the common, frontoparietal control network represent attentional priority to spatial locations, features and objects.

Besides the frontoparietal network, parts of the thalamus have been associated with modulatory signals mediating attentional selection. In a single case study, a patient with a right thalamic lesion including the pulvinar nucleus performed a partial report task, where red target letters have to be reported, while green distractor letters have to be ignored. This patient showed lateralised attentional weighting towards the targets in the ipsilesional field (Habekost and Rostrup, 2006). The authors interpreted the single case findings within the framework of the theory of visual attention (TVA), which states that the topographically organised priority map with stored attention weights is represented in the pulvinar nucleus of the thalamus (Bundesen et al., 2005, 2011). In the same study, patients with lesions outside the thalamic area showed a similar impairment as the single case. However, the non-thalamic lesions were large, including the basal ganglia, the frontal cortex and in some cases extended to the temporal and parietal cortices and, therefore, might have incorporated parts of the frontoparietal network, which is associated with feature- and spatial based attention as described above. In a subsequent study, 16 patients with different thalamic lesions to the right or left hemisphere performed the partial report task (Kraft et al., 2015). Patients did not suffer from neglect or other attentional disturbances as shown by standard clinical testing. The left pulvinar damage of one patient replicated the finding of a spatial attention bias to the ipsilesional side. Medial thalamic damage in 9 of the patients was related to biased attention weights either to the ipsi- or to the contralesional side and the remaining lateral thalamic lesion patients showed a deficit in processing speed and no bias of weights (Kraft et al., 2015).

Further support for attentional weighting bias in patients with pulvinar lesions comes from a study by Snow et al. (2009). Participants were asked to discriminate the orientation of a lateralised target grating in the presence of distractors with varying salience. Compared to controls, patients were impaired in discriminating target features, but only if targets were presented together with highly salient distractors. The deficit was stronger in the contralesional than in the ipsilesional field. The perceptual salience of the distractors competed with the behavioural relevance of the target. The results suggest that the pulvinar plays an important role in filtering irrelevant but salient distractors by representing high attention weights for targets and low weights for distractors. Snow and colleagues (2009) point out that the thalamus is reciprocally connected to the frontoparietal network and visual areas. They argue that the frontoparietal network coordinates attentional selection signals in visual areas via the thalamus. Thus, damage to the pulvinar disrupts the coordination of attentional feedback signals resulting in contralesional impairment in filtering salient distractors (Snow et al., 2009; Strumpf et al., 2013). Analogously, a study in non-human primates underlines the critical role of the pulvinar in attentional selection. The macaques' performance in colour discrimination at a cued location was impaired in the presence of a distractor when the pulvinar had been unilaterally deactivated via muscimol injections. In contrast, the target colour was correctly identified in trials without competing distractors (Desimone et al., 1990).

In sum, the reviewed evidence suggests that parts of the thalamus generate modulatory signals mediating attentional selection. This has been tested using paradigms that rely on a combination of feature- (e.g. colour or orientation) and spatial-based attention. However, the role of the thalamus in solely feature-based or spatial-based attention has not specifically been addressed yet. It remains unclear, whether the thalamus is involved in different types of selective attention as has been demonstrated for the frontoparietal network.

The aim of the current study was to investigate feature- and spatial-based attention in stroke patients with thalamic and non-thalamic lesions. To this end, we applied a variant of the Sustained Attention to Response Task (SART; original version by Robertson et al., 1997), a go/no-go task based on a feature (i.e. colour) or a spatial selection criterion of relevant stimuli. Participants were asked to respond to task-relevant stimuli, while ignoring simultaneously presented task-irrelevant stimuli (i.e. distractors), which could be highly salient or low salient. Subjects with high abilities of feature- and spatial-based attention should be less influenced by the presence of a distractor and show similar performance in low and highly salient distractor trials. Thus, the task requires sustained attention across trials and selective attention to select the relevant stimuli.

Our SART variant differs from the standard approach to investigate feature-based selective attention. Most findings are based on tasks, where one or several targets are presented among multiple distractors throughout the visual field, e.g. visual search tasks (e.g., Gillebert et al., 2012). Hence, a combination of spatial- and feature-based attention is necessary for attentional selection (e.g., Baldassi and Verghese, 2005; Egner et al., 2008; Malhotra et al., 2009; White et al., 2015). The new SART version was designed to disentangle feature-based and spatial-based attention while maintaining the same stimulus type and to avoid a potential confound of both selection types. Two stimuli are shown at once and are either overlapping (separable by colour) or spatially apart (separable by location). Also, the new SART variant is a selective attention task against a sustained attention baseline (Liu, 2003; Molenberghs et al., 2007; Shomstein and Yantis, 2004; Vandenberghe et al., 2001a; Yantis et al., 2002). Most of the prior research on spatial- or feature-based attention made use of cueing tasks or whole/partial report tasks in which trials are separated by a fixed or random intertrial interval. However, in everyday life, the attentional priority map is *continuously* updated based on changes in the spatial location, the features, the sensory salience and the behavioural relevance of stimuli in the environment. The new SART variant enabled us to study the dynamic calibration of attentional priorities, while controlling for processes related to maintaining attention over time.

2. Methods

The study was approved by the Medical Science Interdivisional Research Ethics Committee of the University of Oxford (MSD-IDREC-C1-2013-41). All participants gave written informed consent in accordance with the Declaration of Helsinki.

2.1. Participants

Six patients with subcortical ischaemic lesions were consecutively recruited via the Oxford Cognitive Neuropsychology Centre of the University of Oxford. Extension into the insula and inferior frontal cortex was permitted based on the known distribution of the vascular territory of the posterior branches of the middle cerebral artery. Exclusion criteria were age above 85 years, pre-existing structural lesions or extensive periventricular or subcortical white matter hyperintensities, presence of hemianopia, colour blindness, insufficient balance to sit autonomously in front of a computer and general inability to understand and perform a computerized perceptual discrimination task.