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"Cognitive and Motor Processes in Visuospatial Attention": Editorial

Cognitive and motor processes in visuospatial attention: An interactionist perspective

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The nature of the interactions between covert mental processes, such as attention and working memory, and the control of overt actions, such as eye-movements, has been of long standing interest and controversy. There is broad agreement that motor control, attention, and working memory do interact, but less consensus on how or why they do. Until now, most work has focused on the interaction between motor control and attention. On this topic, different viewpoints have been advanced. For example, at one end of the spectrum lie theoretical approaches such as Rizzolatti's Premotor Theory (Rizzolatti, Riggio, Dascola, & Umilta, 1987) which argued that covert attention is functionally equivalent to the programming of actions such as saccadic eye-movements. At the other end, scholars such as Klein (Klein, 1980; MacLean, Klein, & Hilchey, 2015) argued for a complete decoupling of action control and attention, while others have argued for partial independence (Belopolsky & Theeuwes, 2012; Casteau & Smith, 2019; Smith & Schenk, 2012). More recently, a new debate about the role of actions, and in particular eye-movements, in the encoding, maintenance, and recall of visual working memory emerged (Aagten-Murphy & Bays, 2019; Heuer, Ohl, & Rolfs, 2020; Van der Stigchel & Hollingworth, 2018).

In 2019 we organised a workshop in Durham, supported by the ESRC, DfG and NWO, to discuss different theoretical positions and potential approaches for translating research findings into applications. Several key themes emerged from this meeting. One fundamental issue that was identified was the need to develop new theoretical frameworks that helped move the discussion away from the notion of strict all or nothing coupling between attention and motor control, as exemplified by Premotor Theory, in favour of a more nuanced, interactionist approach that sought to understand the conditions under which the motor system could exert and influence attention and memory. A second was the need to differentiate between ‘premotor’ shifts of attention that occur in the moments before a movement, and truly ‘covert’ attention shifts that occur in the absence of any overt movement. A third theme also emerged, focused on the nature of the interaction between motor control and *non-spatial* attention. This interaction appears to be less understood than the interaction between motor control and *spatial* attention and is an area ripe for exploration. Finally, much discussion centred on the neuropsychology of attention and action, with an emphasis on developing a better understanding of how the complex relationship between attention and the motor system might express itself in different disorders. These four themes are also reflected in the papers published in this special issue.

Three of the papers in the SI are primarily theoretical. Olivers and Roelfsema (2020) focus on the interactions between attention, action and visual working memory (VWM), arguing that VWM acts not simply as a storage system for past

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information, but as a workspace for coupling sensory and motor representations in the service of action. In this view, attentional selection emerges as a consequence of the association of action plans with VWM representations, rather than being the driver of these couplings. By conceptualising attention as an emergent property of action-memory couplings they seek to integrate a range of different findings, while avoiding the type of 'circularity', whereby attention is at the same time described as an influence on and a consequence of Redden, MacInnes, and Klein (2021) report the development of a computational model of Inhibition of Return, which elegantly accounts for the differing inhibitory aftereffects of covert attention and eye-movements. The key point of the paper was to demonstrate that two forms of IOR; a perceptual input form characterised by inhibition of sensory processing, and a motor output form characterised by inhibited responding - are accounted for by different drift–diffusion parameters, thus providing a way of reconciling a range of diverse findings in this literature. The article by Redden and colleagues starts with empirical findings and then develops a computational model of attention. In contrast the final theoretical paper by Tsotsos, Abid, Kotseruba, and Solbach (2021) pursues the opposite strategy. They start with a description of the computational demands needed for a mechanism of attentional control and then suggest ways in which the brain might address those demands. Together these three papers provide a novel framework for understanding the interactions between action, attention and memory.

A number of the empirical contributions explored presaccadic attention. Kreyenmeier, Deubel, and Hanning (2020) applied the Theory of Visual Attention (Bundesen, 1990) to investigate whether premotor attention could be allocated to multiple effector endpoints in parallel. By comparing attentional capacity at the goals of simultaneously executed saccades and reaching movements they were able to demonstrate that attention could indeed be allocated to multiple motor goals in parallel. However, this parallel processing did come at a cost to endogenous orienting, suggesting that pre-motor attention and endogenous attention draw on the same attentional resource. In contrast to Kreyenmeir's work on the effector specificity of pre-saccadic attention, Kroell and Rolfs (2021) focus on the non-spatial characteristics of pre-saccadic attention. They use a psychophysical approach to demonstrate that saccade preparation reshapes the profile of observers' sensitivity to high spatial frequencies. It is this reshaping that drives improved sensitivity, rather than a general enhancement across all spatial frequencies, which they argue reflects an attempt by the visual system to approximate the foveal resolution during the presaccadic period in the service of perceptual stability. Shurygina, Pooresmaeili, and Rolfs (2021) also explore the non-spatial aspects of pre-saccadic attention by asking whether presaccadic attention is modulated by Gestalt principles of grouping. Consistent with earlier experimental evidence demonstrating automatic capture of covert attention by whole objects (e.g., Egly, Driver, & Rafal, 1994), Shurygina and Rolfs show that pre-saccadic attention also yields to object-capture based on Gestalt principles. Pre-saccadic attention was also the focus of the neuroimaging paper by Huddleston, Swanson, Lytle, and Aleksandrowicz (2021), in which they adopted an individual differences approach to tease apart the neural substrates of endogenous covert attention and pre-saccadic attention. Contrary to previous neuroimaging studies, Huddlestone et al. report a high degree of independence between voxels activated by saccade programming, and voxels activated by covert attention, in the parietal lobe (only 22–29% overlap). While these activation patterns were highly consistent within individuals there was also a high degree of variability *across* individuals, and they argue that previous observations of a high degree of overlap between saccade planning and covert attention (e.g., Corbetta et al., 1998) may be an artefact of averaging across individuals. These data go some way to resolving the discrepancy between the experimental and neuropsychological studies arguing for a dissociation between endogenous attention and saccade programming (Casteau & Smith, 2020; Klein & Pontefract, 1994; Smith, Rorden, & Jackson, 2004; Smith, Rorden, & Schenk, 2012) and the imaging work which typically reports associations between the processes (e.g., de Haan, Morgan, & Rorden, 2008). Finally, Jurewicz, Paluch, Wolak, and Wróbel (2020) explored the cortical networks underlying spatial and non-spatial shifts of attention, arguing that reorientation of spatial and non-spatial attention are actually served by different neural networks. Together, these papers offer new insights into the mechanism underlying the coupling between (spatial and non-spatial) attention and motor control.

In the time before a saccade is programmed, attention already plays an important role in the anticipation of the upcoming response. Two papers examined these preparatory processes. Di Russo et al. (2021) focused on the preparatory brain activity while participants performed a sustained and a transient attention task. They observed that cognitive endogenous control was responsible for the attentional modulations but only in sustained tasks, thereby supporting the notion that sustained attention tasks are largely under the influence of top-down guidance. Furthermore, Notaro and Hasson (2021) studied whether predictions of target-location and target-category interact during the earliest stages of attentional orientation. Their results indicate a strong interaction between foreknowledge of object location and semantics during stimulus-guided saccades, and suggest that statistical regularities in an input stream can impact anticipatory, non-stimulus-guided processes. Addleman, Legge, and Jiang (2021) also examined the effect of learning on attention, using a simulated central scotoma to explore the effect of central vision loss (CVL) on implicit attentional learning. Their results show that while simulated scotoma impaired implicit attentional learning it did not interfere with attentional guidance. The authors argue that implicit location probability learning might not involve the oculomotor priority maps that are utilised in goal-driven and stimulus-driven attention. These studies reveal yet another dimension of motor control that deserves further research.

Whilst most of the papers in the current issue focused on the programming of eye-movements, two papers offer insights into how arm movement programming affects attention. Goal directed arm movements are typically preceded by an eye movement and it is assumed that the processes underlying both are coupled (Belopolsky & Theeuwes, 2012).

Arkesteijn, Donk, Belopolsky, and Smeets (2021) explored this coupling by looking at the effect of an irrelevant distractor on the endpoint of a hand movement. They observed that, contrary to previous findings looking at the effect of irrelevant distractor on saccade endpoint (Findlay, 1982), an irrelevant distractor did not affect hand movement endpoint. This led the authors to conclude that eye and hand movements systems might not be as rigidly coupled as previously thought. Wispinski et al. (2021) looked at the coordination between visual and motor system by investigating how dynamic signals can be used to make predictions about the probability of an upcoming target location. They observed that movement trajectories reflected the future probability information, suggesting an integration of visuo-spatial information to effectively guide future actions. A third paper in this domain directly compared eye-movements and manual response in the attention network task (ANT). **Gorina et al**. observed that alertness; orienting and executive control networks were activated whether participants did a manual or a saccade task, but that the interaction between these networks differed depending on the task. The key observation was that alerting enhanced orienting in manual responses but interfered with orienting in saccadic responses. This work offers a new methodology to study visual attentional networks.

A number of submissions aimed to translate the theoretical insights into the links between attention, memory and motor control into clinical applications. Two of these studies focused on the links between attention and action during goal directed action. Aguilar Ros, Mitchell, Ng, and McIntosh (2021) used a dual task paradigm to test the role of attention in the programming and control of reaching movements. They report that attentionally demanding tasks delay the onset of visually guided action, and bias their endpoints towards where the eyes are fixated. These errors are akin to the ‘magnetic misreaching’ observed in patients with optic ataxia (Carey, Coleman, & Della Sala, 1997), and Aguilar-Ros et al. argue that attention problems in optic ataxia may to some extent account for the impaired motor behaviour in this disorder. Arthur et al. (2021) tested the widely held view that Developmental Coordination Disorder (DCD) is associated with a decoupling of attention and action, such that children with DCD are unable to predictively coordinate their eye-movements with their hand movements. Contrary to this idea they report no evidence that children with DCD are any less coordinated than children without DCD. They attribute their observation to the fact that the task used in their study was more interesting and less frustrating that the tasks typically used in studies on DCD patients. In related work, Ten Brink, Halicka, Vittersø, Keogh, and Bultitude (2021) explored spatial biases in attention and action, but here the focus was on whether Complex Regional Pain Syndrome (CRPS) produced biases of spatial attention away from the affected limb. They observed no such bias and concluded that previous reports of neglect-like symptoms in CRPS actually reflect a distorted body representation, rather than distorted attentional orienting.

Two papers were concerned with the rehabilitation of hemispatial neglect, a complex disorder characterized by lateralized impairments of visual attention in the absence of motor or sensory deficit. Elshout, Van der Stigchel, and Nijboer (2021) explored the idea that the motor-induced attentional shift may be amplified if two instead of just one effector system will be involved in the goal-directed movement. They exploited this idea in a modified visual scanning training, a training method widely used in clinical practice to ameliorate symptoms of hemispatial neglect. In this new version of visual scanning training, a congruent movement (eye and pointing movement) has to be executed to the same location. Attenuation of neglect symptoms was indeed found in the subacute phase of neglect, indicating the clear potential of such a training protocol. Ludwig and Schenk (2021) used a gaze-contingent display to penalize eye-movements to one side. Healthy participants took part in a visual search paradigm. In the case of eye-movements to the penalized half, the stimuli on that half disappeared. It was found that eye-movements into the penalized hemifield decreased in frequency during the training. The effect was observed in attentional tasks not used during the training. Furthermore, repetition of the training led to effects that lasted for several days following the end of the training. Ludwig et al. argued that this training holds promise for treating the exploration deficit in patients with unilateral neglect. In related work Terruzzi et al. (2021) examined the time course of prism adaptation and its aftereffects in healthy participants, demonstrating that prism adaptation primarily operates in an egocentric reference frame, thus making it most suitable for the neuro-rehabilitation of patients with egocentric, rather than allocentric from of neglect.

Two papers adopted a neuropsychological approach to attention and motor control in neurodegenerative diseases. Smith, Casteau, and Archibald (2021) examined the coupling of attention and oculomotor control in Progressive Supranuclear Palsy (PSP), reporting that patients presented with significantly impaired on feature search and spatial short term memory compared to patients with Parkinson's disease (PD). As these deficits were most pronounced along the vertical meridian, which coincided with the vertical paralysis of gaze that is characteristic of PSP but not PD, they conclude that the oculomotor dysfunction drives a deficit of attention in PSP. Smith and colleagues propose that deficits of visual search and short term memory may be a potentially useful diagnostic marker for PSP. Polden and Crawford (2021) investigated the Inhibition of Distracter Effect (IRD) in a large sample of patients with Alzheimers disease and mild cognitive impairment for European and Asian populations. They report that the IRD is present across all ethnicities, age groups and patient cohort and argue that the preservation of the IRD in patient population support the dissociation between inhibition of gaze and inhibition of spatial location. The article by Aziz, Good, Klein, and Eskes (2021) takes a slightly different tack by focusing on the role of VWM in the guidance of visual attention during search. The key observation here was that the role of WM in visual search varied with age, such that providing a search template attenuated the relationship between WM capacity and search times in younger adults but not older adults. Aziz et al., propose that providing a search template can reduce WM demands, but only when the observer has sufficient attentional capacity to process both the search template and engage in attentive search, indicating the importance of understanding how cognitive processes vary with ageing when developing cognitive interventions for neurodegenerative diseases that primarily affect older people.

The collection of papers in the SI illustrate the diverse range of theoretical positions, methodological approaches and sample populations that can be used to investigate the interactions between attention, memory and motor control. The range and quality of the work is a testament to the resilience of all the contributors in the face of the huge challenges faced during the coronavirus pandemic and we are also very grateful to the many reviewers who made time in their busy schedules to provide thoughtful and constructive reviews. Many of the articles are available open access, as are the vast majority of the data, and we invite interested readers to explore these resources. It is evident from these papers that understanding the interactions between the motor system and cognitive functions (such as attention and visual working memory) is crucial to reveal the functional relevance of the different cognitive functions. Goal-directed behaviour is crucial for the interaction with our environment, and therefore a complete understanding of visual working memory can only be revealed when taking an action perspective. Similarly, the functional relevance of attention is best understood in the context of action and motor control. In our view, this interactionist approach is moving the field towards a higher ecologically validity and will be a fruitful avenue for future research.

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