Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Issue: *Competitive Visual Processing Across Space and Time*

# Introduction to *Competitive Visual Processing Across Space and Time: Attention, Memory, and Prediction*

According to the biased competition framework,[1–3] competition, selection, and priority control are essential processing characteristics of the brain. For instance, in the visual modality, only a limited number of objects and features from a single eye fixation are available for perception, action, and memory. In one interpretation of this framework, competition between visual objects is biased by attentional resources that are distributed according to priorities.[4,5] Thus, factors controlling priority, such as the current task or salience of environmental information, play a crucial role in selective visual processing across space and time. In this view, selective processing is an emergent property of attentional processes.

Recently, interactions of memory with attentional selection processes in vision have become a key topic in cognitive neuroscience. First, the relationship between visual working memory and selective visual processing seems to be bidirectional.[6,7] On the one hand, working-memory contents are often assumed to result from preceding competitive visual processing. A stronger version of this claim states that acting on visual information presupposes its working-memory representation.[8] In any case, competitive visual processing determines the probability of representations in working memory. On the other hand, contents of visual working memory can bias ongoing competitive visual processing.[9] Under certain conditions, currently encoded visual working-memory objects modulate which new sensory objects will reach the highly restricted "space" of working memory. For instance, several studies have shown that efficiency in a visual-search task can be influenced by working-memory contents that are retained for different concurrent tasks.[6]

Second, the same type of argument has been formulated for the role of long-term memory and knowledge in visual attentional selection. On the one hand, it has been claimed that long-term memory encoding of environmental information presupposes its attentional selection and working memory encoding.[2] On the other hand, long-term memory has been considered one important origin of control signals that bias ongoing competitive visual processing.[10] One form of such a long-term memory bias refers to context information. A context-based biasing signal can, for instance, come from a constant target template in a visual-search task, or from semantic and syntactic knowledge biasing selection during reading. In each case, long-term memory information is used for biasing visual competition. Moreover, selection in the sense of retrieving information from long-term memory has been considered as an attentional process.[2]

Third, based on working and long-term memory representations, predictions play a crucial role in biasing competitive visual processing in space and time.[11–13] Findings from the Posner cueing paradigm[14] are an example in which location expectations guide attentional selection.[4] Moreover, violations of predicted context information (e.g., unexpected objects in a certain scene or a task sequence) are another factor influencing attentional selection.[15] Several lines of evidence demonstrate that unexpected visual events influence the allocation of attentional priority in space and time.[16,17]

*Competitive Visual Processing Across Space and Time: Attention, Memory, and Prediction* is based on talks of the closing conference of the ZiF research group "Competition and priority control in mind and

doi: 10.1111/nyas.12744

brain: new perspectives from task-driven vision" (March 2013, organized by the editors of this issue, see http://www.uni-bielefeld.de/%28en%29/ZIF/FG/2012Priority/). The articles consequently focus on the three memory-related aspects of competitive visual processing explicated above: interactions of attention and working memory, interactions of attention and long-term memory, and interactions of attention and prediction.

Several studies in this issue address the interplay of working memory and attentional selection. Van Moorselaar, Battistoni, Theeuwes, and Olivers study the speed at which working-memory contents can bias perceptual selection. They demonstrate that cueing an item in working memory can exert biases on *covert* attentional selection extremely rapidly, on the order of 100–200 milliseconds.[18] Hollingworth addresses effects of working memory on overt attentional shifts—that is, on oculomotor selection. He demonstrates that rapid saccades are biased toward object regions that have featural overlap to the item retained in working memory, supporting rapid effects of working-memory content on overt attentional selection.[19] Complementary to such attentional and perceptual effects, Souza, Rerko, and Oberauer study the effect of "internal attention" on working memory itself. They developed a novel paradigm to quantify how directing internal attention to an item in working memory "refreshes" its representation—that is, how attention protects the item against forgetting.[20] To address the representational format of working-memory contents, Töllner, Mink, and Müller combine an EEG measure with behavioral measures. They conclude that there are three hierarchical stages of memory representation, representing objects, dimensions, and features, respectively.[21]

Foerster and Schneider examine the effect of long-term memory on selection in a task that requires learning and reproducing an action sequence. Specifically, they ask how overt attentional control by long-term memory is interrupted in the face of an unpredicted target-sequence change, and find evidence for a shift from memory-based selection to visual search.[22] Becker and Lewis examine how memory-based biases and perception-based biases interact in their influence on competitive processing of visual stimuli. They show that attention capture by visual onsets is modulated by competition and feature-based attention but not by perceptual salience as such.[23]

Võ and Wolfe review the role of memory for guiding visual search in organized real-world scenes where episodic and semantic information retrieved *from* memory is used to decide which locations in space are prioritized for fixation selection.[24] Conversely, Nuthmann and Einhäuser study the selection of fixated locations *for* memorization, introducing a novel method that allows quantification of each image feature's *unique* contribution to fixation selection during natural-scene viewing.[25]

The role of prediction for attention is evident in overt attentional shifts, since the retinal input inevitably changes as a consequence of a saccadic eye movement. Herwig, Weiß, and Schneider examine the role of prediction across saccadic eye movements. They show that not only sensory information, but also information retrieved from memory shapes predictions about the sensory consequences of such movements.[26] Conversely, Horstmann examines the evidence for attention to unpredicted stimuli and argues for a surprise–attention link in which stimuli that deviate from expectation are prioritized for selection.[27] To incorporate predictions and expectations into their "theory of visual attention" (TVA), Bundesen, Vangkilde, and Habekost model visual bias as the product of subjective prior expectation, utility (importance), and the general level of alertness. This provides a formulation of TVA that is consistent with an ideal observer model and offers a Bayesian interpretation of TVA.[28]

Besides competition for processing resources, selection may also manifest itself as resolving competition for awareness. Eitam, Shoval, and Yeshurun examine the relationships between phenomenal consciousness, task-dependent biases, and memory encoding. Using Kanizsa figures, they confirm that phenomenal experience (of an illusionary contour) is possible without recognition (of the inducer). Importantly, such relevance-based selection is not possible when both attributes (experienced and recognized) belong to the same object.[29] As an alternative measure for access to perceptual awareness, Marx, Gruenhage, Walper, Rutishauser, and Einhäuser use dominance in rivalry. They demonstrate that a neuronal model that forms a memory state predicts the distribution of such dominance over time better than alternative models without memory, thereby linking competition for awareness to memory.[30]

In addition to the multifaceted behavioral links between attention on the one hand and working memory, long-term memory, and prediction on the other hand, several studies in this issue address neural substrates of such interactions. Zelinsky and Bisley review the concept of priority maps for attentional guidance. Specifically, they analyze the interplay between priority maps and their interaction with working memory, and suggest that goal states that are maintained in visual working memory are used to construct several priority maps, which in turn control the various motor systems.[31] In a study of four patients with Bálint–Holmes syndrome, Pisella, Biotti, and Vighetto dissociate deficiencies in covert attentional orienting from deficiencies in overt exploration behavior. The latter is suggested to result from deficiencies in maintaining an overt-attention-guiding salience (priority) map across saccades and to be associated with right inferior parietal damage.[32] Kasper, Grafton, Eckstein, and Giesbrecht combine EEG and fMRI to probe contextual cueing, in which learned stimulus configurations speed up target selection. They show that attentional processes interact with hippocampus-related memory both for short- and long-term implicit learning.[33] Trapp and Bar review evidence that predictive top-down activation biases competitive processing in favor of the correct stimulus interpretation, and suggest the orbitofrontal cortex as a neural substrate for such computation.[34]

Together, the papers presented in this issue suggest that task-adequate and goal-directed control of competitive visual processing—the function of attention—emerges from interactions of various memory and prediction systems with sensory input.

This issue of *Annals of the New York Academy of Sciences* resulted from the research group that resided in 2012–2013 at the Centre for Interdisciplinary Research (ZiF) in Bielefeld, Germany, Bielefeld University's Institute of Advanced Studies. We are very grateful to all members of the ZiF groups and the numerous other researchers that came to the ZiF and contributed to this great research year. We also cordially thank Britta Padberg and her exceptional team for the splendid hospitality during this year. The papers presented in this issue are based on invited contributions to the closing conference of the ZiF research group in March 2014. Additional support for the hosting of the conference was provided by the Cluster of Excellence Cognitive Interaction Technology (CITEC). Finally, we thank the reviewers for their high-quality comments and quick turnaround times that were essential to the quality and timeliness of this issue.

Werner X. Schneider
*Neuro-cognitive Psychology, Department of Psychology*
*Centre for Interdisciplinary Research*
*Bielefeld University, Bielefeld, Germany*

Wolfgang Einhäuser
*Centre for Interdisciplinary Research, Bielefeld University, Bielefeld, Germany*
*and Neurophysics, Philipps-University Marburg, Marburg, Germany*

Gernot Horstmann
*Neuro-cognitive Psychology, Department of Psychology*
*Centre for Interdisciplinary Research*
*Bielefeld University, Bielefeld, Germany*

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