Summary

In previous work we modelled object-based attention in the temporal cortex [1,2] and visual working memory in the prefrontal cortex [3,4]. By integrating these models of object-based attention and working memory with a model of spatial attention in the parietal cortex, we aim to arrive at a "closed-loop attention model" (CLAM). The purpose of CLAM is to model attentional phenomena such as visual search.

Visual search consists of finding a target within a multitude of objects, or distractors [5]. Sometimes a target 'presents' itself (i.e., an 'oddball'), but often the target is stored in working memory. An influential model of visual search is the Feature Integration Theory (FIT) [6]. In FIT, visual search proceeds in two stages; a preattentive stage and an attentive stage. In the preattentive stage, elementary stimulus features (color, motion, size, orientation) are processed in parallel. In this stage, an oddball like a red object on a green background is detected forthwith. But more complex targets can only be found in the second attentive stage of the model. In contrast with the preattentive stage, the attentive stage operates in a serial manner, by selecting obects in sequence until the target is found. The objects are selected by spatial attention, that is, by selecting a particular position in the visual field.

In CLAM, the preattentive and attentive stages are integrated, in line with experimental findings that do not support a clear distinction between preattentive and attentive processing [5]. Furthermore, in contrast with FIT, selection can result from any of the processed stimulus features (color, shape, motion, position), including complex features such as whole shapes. Processing in CLAM starts in the lower retinotopic areas of the visual cortex (e.g., V1-V4). Neurons in these areas have relatively small receptive fields and they typically encode conjunctions of elementary visual features. For instance, elementary conjunctions of shape (e.g., orientation) with color, or of shape with motion (such as an oriented bar moving in a particular direction). Because the areas are retinotopic, neurons encode for position as well. From these lower areas, two pathways emerge in CLAM. The 'ventral' pathway processes shape and color identity (as in the temporal cortex), and the 'dorsal' pathway processes position information (as in the parietal cortex). In CLAM, both pathways consist of a combination of a feedforward network and a feedback network, which interact locally [1].

Overall interaction between the ventral and dorsal pathway occurs in the lower areas V1-V4. For instance, the selection of the (whole) shape or the color of a target object in the ventral pathway results in enhanced activation in V1-V4 on the position of the target. In this way, the position of the target can be selected in the dorsal pathway [1]. Conversely, selection of a position in the dorsal pathway will enhance activation on that position in the areas V1-V4, which results in the selection of the shape and the color of an object on that position in the ventral pathway. In this way, V1-V4 functions as a 'blackboard' [3] in which the features of an object (shape, color, motion, position) can be related (or bound).

The ventral and dorsal pathway in CLAM also project (feedforward) to the prefrontal cortex (PFC). Here, the features of a target object (or objects) are stored in a 'blackboard'

working memory [3,4]. The 'blackboard' in PFC is similar to the 'blackboard' in visual cortex (V1-V4) and it is also used to bind the features (shape, color, position) of an object. The working memory in PFC projects back to the ventral and dorsal pathway.

Thus, CLAM consists of four 'parts': V1-V4, ventral pathway, dorsal pathway and PFC. These parts are connected in a 'diamond' structure, with reciprocal connections between (V1-V4) - ventral pathway - PFC and between (V1-V4) - dorsal pathway - PFC. In this way, the diamond connection structure of CLAM forms a closed loop.

Visual search results from the dynamic interactions in the diamond connection structure of CLAM. A target in PFC will influence the ventral pathway (if the target is a shape or color) or the dorsal pathway (if the target is a position). The ventral or dorsal pathway then interact with the processing of the stimulus display in V1-V4. If the target is unique, this interaction will result in the selection of the activation related to the target in V1-V4 (as with an oddball). In turn, this will produce the selection of all other features of the target (in the ventral or dorsal pathway). However, if there are too many objects in the blackboard V1-V4, the interaction will not succeed [4]. Furthermore, if the target consists of a conjunction of features (e.g., a particular shape-color combination), then the interaction will likely select more than one object in V1-V4. In these cases, a serial process is needed to select the target. In CLAM, this serial process is position-based (as in FIT). It consists of preselecting a region in V1-V4, in which the interaction process described above occurs. This serial process continues until the target is selected. The search times of this process are similar to the search times reported in the experimental literature [5].

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