A Bio-inspired Architecture of an Active Visual Search Model

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Abstract. A novel brain inspired cognitive system architecture of an active visual search model is presented. The model is multi-modular consisting of spatial and object visual processing, attention, reinforcement learning, motor plan and motor execution modules. The novelty of the model lies on its decision making mechanisms. In contrast to previous models, decisions are made from the interplay of a winner-take-all mechanism in the spatial, object and motor salient maps between the resonated by top-down attention and bottom-up visual feature extraction and salient map formation selectively tuned by a reinforcement signal spatial, object and motor representations, and a reset mechanism due to inhibitory feedback input from the motor execution module to all other modules. The reset mechanism due to feedback inhibitory signals from the motor execution module to all other modules suppresses the last attended location from the saliency map and allows for the next gaze to be executed.

Keywords: Visual search, cognitive system, dopamine, saliency, ART, decision making, attention, perception, action, reinforcement learning.

1 Introduction

Visual search is a type of perceptual task requiring attention. Visual search involves an active scan of the visual environment for a particular object or feature (the target) among other objects or features (the distracters). Visual search can take place either with (active visual search) or without (passive visual search) eye movements.

Attention has been described as the control system in prefrontal cortex (PFC) whose role is to generate a top-down signal which will amplify specific target (spatial and/or object) representations in the posterior dorsal and ventral cortex, while at the same time will inhibit those of distracters [26]. Many computational theories of visual attention have been proposed over the years [13,14,15,16,17,18,19,20,21,22]. Some of these models [14,21] emphasized the formation of a bottom-up saliency-map that biases attention. According to these models scanpaths (sequences of saccadic eye movements) are generated according to the value of saliency in the map. That means that saccades are generated first

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towards the most salient object in the map, next towards the second most salient object and so forth. On the other hand, other models emphasized the need of the interplay between a bottom-up visual feature extraction module (the "what" and "where" pathways) and a top-down attention selective module (the PFC) to drive attention to specific regions-of-interest (ROIs) [13,17,18,20,22]. However, most of these studies failed to show the mechanisms by which the PFC attentive processes are recruited in order to guide attention in posterior and lower-level cortical areas.

The goal of the present study is to present a biologically plausible cognitive system architecture of active visual search model. The model comprises of many modules with specific as well as distributed functions and it is heavily supported by neuroscientific experimental evidence. Its novelty lies on its proposed distributed decision making mechanisms, whose functions rely on the coordinated actions of its visual, attention, reinforcement teaching, motor plan and motor execution modules.

2 Proposed Architecture

The proposed architecture of the active visual search model (see Figure 1) is multi-modular, consisting of a visual processing module, an attention module, a

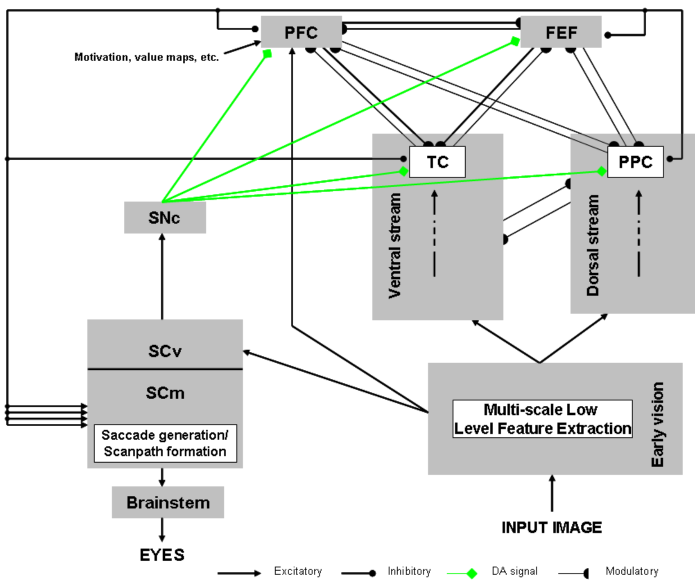

Fig. 1. Proposed multi-modular and their corresponding brain areas active visual search model. PFC: prefrontal cortex; FEF: frontal eye fields; PPC: posterior parietal cortex; TC: temporal cortex; SCv: visual superior colliculus; SCm: motor superior colliculus; SNc: substantia nigra pars compacta; DA: dopamine. See text for the corresponding to the model's modular functionality of each brain area.

decision-making module, a reinforcement learning module, a motor plan module and a motor execution module. In the following section, I will describe each module, its functionality and will provide experimental evidence for its validity. Finally, I will describe the stages of information processing from the presentation of the input image till the execution of an eye movement (see Figure 2).

2.1 Modules

Spatial and object visual processing module. The visual processing module up to the formation of global saliency maps in both the dorsal (space) and ventral (object) streams is the same as in [13,21]. Its functionality is to decompose an input image through several pre-attentive multi-scale feature detection mechanisms (sensitive to color, intensity and orientation) found in retina, lateral geniculate nucleus (LGN) of the thalamus and primary visual cortical area (V1) and which operate in parallel across the entire visual scene, into two streams of processing, that is the dorsal for space and the ventral for object. Neurons in the feature maps in both streams then encode the spatial and object contrast in each of those feature channels. Neurons in each feature map spatially compete for salience, through long-range connections that extend far beyond the spatial range of the classical receptive field of each neuron. After competition, the feature maps in each stream are combined into a global saliency map, which topographically encodes for saliency irrespective of the feature channel in which stimuli appeared salient [13,14]. In the model, the global spatial saliency map is assumed to reside in the posterior parietal cortex (PPC), whereas the global object saliency map resides in the ventral temporal cortex (TC). The speed of visual information processing from the early multi-scale feature extraction in the retina till the formation of global saliency maps in the dorsal PPC and ventral TC is 80-100ms [[27] and references therein].

Attention module. The attention module is represented by prefrontal cortex (PFC) cells. It receive a direct input visual signal from the early stages of visual processing (retina, LGN, V1) as well as from the FEF (motor plans), PPC (spatial representations), TC (object representations) and other brain areas (motivation (medial PFC), value representations (orbito-frontal cortex (OFC); medial PFC and OFC neuronal responses are not modeled in this study). Its role is to send feedback signals to every stage of the visual processing module, which will amplify specific neuronal responses throughout the visual hierarchy [26] as well as to the selectively tuned via the reinforcement learning DA signals target (spatial and object) and motor plan representations in the PPC, TC, and frontal cortices (FC), while at the same time will inhibit those of distracters.

Reinforcement learning module. At the same time and in a parallel manner, the retinal multi-scale low level features propagate to the upper layers of the superior colliculus (SC), which in turn provide the sensory input to the substantia nigra pars compacta (SNc) and ventral tegmental area (VTA). Recent neuroanatomical evidence has reported a direct tectonigral projection connecting the deep layers of the superior colliculus to the SNc across several species

[7,10,11]. This evidence is confirmed by neurophysiological recordings in alive animals [8,23].

The SNc and VTA comprise the reinforcement learning module of the model. Both SNc and VTA contain the brain's dopaminergic (DA) neurons, which have been implicated in signaling reward prediction errors used to select actions that will maximize the future acquisition of reward [9] as well as the progressive movement deterioration of patients suffering from Parkinson's disease [1,2,5]]. The conduction latency of the signal from the retina to SC and from there to SNc is 70-100ms, whereas the duration of the DA phasic response is approximately 100ms [12].

The SC activated SNc DA neurons broadcast reinforcement traching signals to neurons in prefrontal cortex (PFC), frontal eye fields (FEF), posterior parietal (PPC) and temporal cortices (TC), but not to visual cortices [[1] and references therein]. An extensive review of the dopaminergic innervation of the cerebral cortex has been recently published by [1]). Briefly, the source of the dopaminergic (DA) fibers in cerebral cortex were found to be the neurons of the substantia nigra pars compacta (SNc) and the ventral tegmental area (VTA). DA afferents are densest in the anterior cingulate (area 24) and the motor areas (areas 4, 6, and SMA), where they display a tri-laminar pattern of distribution, predominating in layers I, IIIa, and V-VI. In the granular prefrontal (areas 46, 9, 10, 11, 12), parietal (areas 1, 2, 3, 5, 7), temporal (areas 21, 22), and posterior cingulate (area 23) cortices, DA afferents are less dense and show a bilaminar pattern of distribution in the depth of layers I, and V-VI. The lowest density is in area 17, where the DA afferents are mostly restricted to layer I.

The role of the DA broadcasting signals is to act as the vigilant parameter of an ART network, which reinforce via selective tuning [1] the relevant according to previously learned experiences to the visual scene responses of cells in the areas they target. All other cells that don't receive or receive reduced DA signals "perish" as their signal-to-noise ratio responses are extremely low (see Figure 7 in [1]).

Motor plan module. In this module, the global spatial and object saliency maps formed in the PPC and TC respectively are transformed in their corresponding global saliency motor plan maps. The motor saliency plan module is assumed to reside in the frontal eye fields (FEF) of the frontal lobes [28]. Reciprocal connections between the PPC, TC and FEF ensure the sensorimotor groupings of the spatial and object representations with their corresponding motor plans [[29] and references therein].

Decision module. The decision to where to gaze next is determined by the coordinated actions of the Attention, Reinforcement Learning, Visual Processing, Motor Plan and Motor Execution modules in the model. More specifically, bottom-up, top-down and reset mechanisms represented by the complex and intricate feedforward, feedback and horizontal circuits of PFC, PPC, TC, FEF, motor SC and the brainstem are making decisions. Adaptive reciprocal connections between (1) PFC and PPC, (2) PFC and TC, (3) PFC and FEF, (4) FEF and PPC, (5) FEF and TC, and (6) PPC and TC operate exactly as the comparison and recognition fields of an ART (Adaptive Resonance Theory) system [24,25].

Briefly, an ART system consists of a comparison field and a recognition field composed of neuronal populations, a vigilance parameter, and a reset module. The vigilance parameter has considerable influence on the system: higher vigilance produces highly detailed memories (many, fine-grained categories), while lower vigilance results in more general memories (fewer, more-general categories). The comparison field takes an input vector (a one-dimensional array of values) and transfers it to its best match in the recognition field. Its best match is the single neuronal population whose set of weights (weight vector) most closely matches the input vector. Each recognition field neuronal population outputs a negative signal (proportional to that neuron's quality of match to the input vector) to each of the other recognition field neuronal populations and inhibits their output accordingly. In this way the recognition field exhibits lateral inhibition, allowing each neuronal population in it to represent a category to which input vectors are classified. After the input vector is classified, the reset module compares the strength of the recognition match to the vigilance parameter. If the vigilance threshold is met, training commences. Otherwise, if the match level does not meet the vigilance parameter, the firing recognition neuronal population is inhibited until a new input vector is applied; training commences only upon completion of a search procedure. In the search procedure, recognition neuronal populations are disabled one by one by the reset function until the vigilance parameter is satisfied by a recognition match. If no committed recognition neuronal population's match meets the vigilance threshold, then an uncommitted neuronal population is committed and adjusted towards matching the input vector.

In this model, as I mentioned before, the ART's vigilance parameter is represented by the broadcasted DA reinforcement teaching signals. High and intermediate levels of DA ensure the formation of fine and coarse categories respectively, whereas low values of DA ensure that non-relevant representations and plans perish.

The reciprocal connections between (1) PFC, PPC and TC, and (2) PFC and FEF allow for the amplification of the spatial, object and motor representations pertinent to the given context and the suppression of the irrelevant ones, whereas the reciprocal connections between the FEF, PPC and TC ensure for their groupings.

Decisions in the model are made from the interplay of a winner-take-all mechanism in the spatial, object and motor salient maps between the selectively tuned by DA and resonated spatial, object and motor representations [3,4,6] and a reset mechanism due to a feedback signal from the SC to FEF [30], PFC, PPC, TC and SNc [12] analogous to the IOR in [13], which suppresses the last attended location and executed motor plan from their saliency maps and allows for the next salient motor plan to be executed.

Motor execution module. The motor plan that has won the winner-take-all competition in the FEF field propagates to the intermediate and deep layers of superior colliculus (SC) and the brainstem (motor execution module), where the final motor command is formed. This final motor command instructs the eyes about the direction, amplitude and velocity of movement. Once, the motor plan arrives in the SC, inhibitory feedback signals propagate from the SC to PFC, FEF, PPC and TC in order to reset these fields and set the stage for the salient point to gaze to. The speed of processing from the input image presentation till the generation of an eye movement is approximately 200-220ms [3].

2.2 Information Processing

Once an input image is presented three parallel and equally fast processing modes of actions are initiated. In the first mode of action (visual processing), pre-attentive multi-scale feature detection and extraction mechanisms sensitive to color, intensity and orientation operating in parallel at the level of the retina, LGN and V1 start to work. From the level of V1 and on the features are separated into two streams: the dorsal for space processing and the ventral for object processing. At the end levels of the visual hierarchy, the PPC and TC lie, where global saliency maps for space and object are formed. In the second mode of action (reinforcement learning), the retinal signal activates the phasic reinforcement teaching (dopamine) signals via the visual layers of the SC. In turn, the phasic DA teaching signals will be broadcasted to the whole cortex (PFC, FEF, PPC and TC) and will selective tune the responses of different neuronal populations in these areas according to previous similar acquired experiences. In the third mode of action (attention), the retinal signal will travel a long distance to PFC, where will activate the recognition neuronal populations. The recognition neuronal populations will send/receive top-down/bottom-up feedback/feedforward signals to/from the spatial, object and motor saliency maps of the PPC, TC and FEF. All three modes of action take the same amount of time (approximately 100ms) [12,27].

In the next step, the spatial and object salient maps will go through a sensory-motor transformation to generate their corresponding motor salient maps at the FEF level. Reciprocal connections between the PPC, TC and FEF will bind the perceptual and motor salient maps together. While this transformation and grouping is taking place, attentional and reinforcing teaching signals from the PFC and SNc respectively will amplify/selectively tune the neuronal responses at the PFC, PPC, TC and FEF levels. A winner-take-all mechanism in these fields will select the most salient and resonated spatial, object and motor plan representation. The selected motor plan will then be forwarded to the motor execution areas (SC and brainstem) where the final motor command will be formed and the eye movement will be generated. The speed of processing from the start of the attentive resonance, selective tuning and motor plan formation, selection and execution takes another approximately 100-120ms (a total of approximately 200-220ms from input image presentation to eye movement execution) [3].

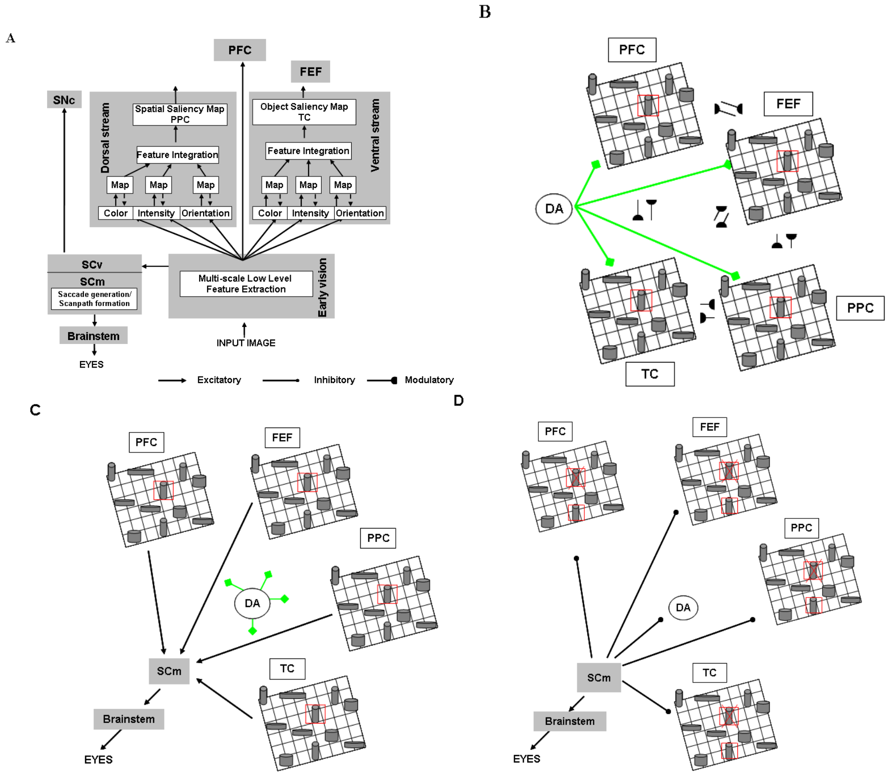

Fig. 2. Information processing stages of the active visual search model. (A) Visual processing stage. Once an input image is presented three parallel and equally fast processing pathways get activated: (1) Visual hierarchy pathways till the level of PPC (space) and TC (object), (2) sensory activated by the SCv SNc (dopamine) system, and (3) direct visual input to PFC. (B) DA broadcasting teaching signals to PFC, PPC, TC and FEF. Different neuronal populations receive different levels of DA. High and intermediate DA values result in "sharp tuned" neuronal responses, whereas low DA values result in "broadly tuned" neuronal responses. Neuronal responses are depicted by gray-colored towers in each brain area. The height of each tower represents the neuronal amplitude activation, whereas the width of each tower represents the degree of tuning. (C) Feedforward activation of the SCm by FEF, PFC, PPC and TC. Red square surrounding the response of a neuronal population represents the winner salient and resonated according to some value of vigilance (DA signal) representation in each brain area. (D) Reset mechanism by feedback inhibitory projections from the SCm to SNc, FEF, PFC, PPC and TC. Reset mechanism prevents previously selected representation (red crossed square) and allows all other resonated neuronal population responses to compete each other for selection. Bottom tower surrounded by red square represents the winner salient and resonated representation. PFC: prefrontal cortex; PPC: posterior parietal cortex; TC: temporal cortex; FEF: frontal eye fields; DA: dopamine; SC: superior colliculus; SCv: visual superior colliculus; SCm: motor superior colliculus; SNc: substantia nigra pars compacta.

Coincidently, Redgrave and Gurney [12] recently reported that the duration of the phasic DA signal (reinforcement teaching signal in this model) is 100ms and it precedes the first eye movement response. That means that the model's assumption about a co-active reinforcing teaching signal with the resonated attention and motor plan selection is valid. All these mechanisms are reset by a feedback excitatory signal from the SC (motor execution module) to the inhibitory neurons of the FEF, PFC, PPC, TC and SNc (all other model modules), which in turn inhibit and hence prevent the previously selected targets, objects and plans from being selected again (see Fig. 2D).

3 Comparison with Other Models and Discussion

A very influential model of visual attention has been put forward by Itti and Koch [13,21]. The model postulated that the decision to where to gaze next is determined by the interplay between a bottom-up winner-take-all network in a saliency map, which detected the point of highest saliency at any given time, and the inhibition-of-return (IOR), which suppressed the last attended location from the saliency map, so that attention could focus onto the next most salient location. However, top-down attentional mechanisms were not explicitly modeled in their model.

A biologically plausible computational model for solving the visual binding problem was developed over the years by John Tsotsos and his colleagues [20,31,32,33,34]. Their "Selective Tuning" model relied on the reentrant connections in the primate brain to recover spatial information and thus to allow features represented in a unitary conscious percept. However, the model fails to show the neural mechanisms by which attention, recognition and grouping work together. An engineering control approach to attention was applied in the Corollary Discharge of Attention Movement (CODAM) model of Taylor and colleagues [18,35,36,37,38]. Their model is multi-modular and has successfully simulated a wide range of visual, working memory, attention and higher level cognitive phenomena.

My model presented herein utilizes similar features with above mentioned models and extends them. Its visual processing module operates the same way as in the Itti and Koch model [13,21]. In contrast to their model, it consists also of an attentional module, whose function is through its re-entrant connections between the PFC, PPC, TC and FEF to amplify the relevant targets, objects and plans to the given context. Re-entrant connections also exist, as in the Selective Tuning model [20], between FEF, PPC and TC whose function is to bind together to a single percept the visuo-motor salient, attentionally resonated and selectively tuned by reinforcement teaching signals representations. The novelty of my model lies on the newly discovered sensory driven DA phasic signal [12], which operates as a reinforcement teaching signal to the neural responses of the PFC, PPC, TC and FEF. The scalar value of this reinforcing signal (vigilant parameter) "determines" by selective tuning [1,2,3] the degree of participation of the various resonated spatial and object salient representations to the formation, selection and execution of motor plans.

References

1. Cutsuridis, V., Perantonis, S.: A Neural Network Model of Parkinson's Disease Bradykinesia. Neural Networks 19(4), 354–374 (2006)
2. Cutsuridis, V.: Does Reduced Spinal Reciprocal Inhibition Lead to Co-contraction of Antagonist Motor Units? A Modeling Study. Int. J. Neur. Syst. 17(4), 319–327 (2007)
3. Cutsuridis, V., Smyrnis, N., Evdokimidis, I., Perantonis, S.: A Neural Network Model of Decision Making in an Antisaccade Task by the Superior Colliculus. Neural Networks 20(6), 690–704 (2007b)
4. Cutsuridis, V., Kahramanoglou, I., Smyrnis, N., Evdokimidis, I., Perantonis, S.: A Neural Variable Integrator Model of Decision Making in an Antisaccade Task. Neurocomputing 70(7-9), 1390–1402 (2007a)
5. Cutsuridis, V.: Neural Model of Dopaminergic Control of Arm Movements in Parkinson's Disease Bradykinesia. In: Kollias, S.D., Stafylopatis, A., Duch, W., Oja, E. (eds.) ICANN 2006. LNCS, vol. 4131, pp. 583–591. Springer, Heidelberg (2006)
6. Cutsuridis, V., Kahramanoglou, I., Perantonis, S., Evdokimidis, I., Smyrnis, N.: A Biophysical Model of Decision Making in an Antisaccade Task Through Variable Climbing Activity. In: Duch, W., et al. (eds.) ICANN 2005. LNCS, vol. 3695, pp. 205–210. Springer, Berlin (2005)
7. Comoli, E., Coizet, V., Boyes, J., Bolam, J.P., Canteras, N.S., Quirk, R.H., Overton, P.G., Redgrave, P.: A Direct Projection from the Superior Colliculus to Substantia Nigra for Detecting Salient Visual Events. Nat. Neurosci. 6(9), 974–980 (2003)
8. Coizet, V., Comoli, E., Westby, G.W., Redgrave, P.: Phasic Activation of Substantia Nigra and the Ventral Tegmental Area by Chemical Stimulation of the Superior Colliculus: An Electrophysiological Investigation in the Rat. Eur. J. Neurosci. 17(1), 28–40 (2003)
9. Schultz, W.: Predictive Reward Signal of Dopamine Neurons. J. Neurophysiol. 80, 1–27 (1998)
10. McHaffie, J.G., Jiang, H., May, P.J., Coizet, V., Overton, P.G., Stein, B.E., Redgrave, P.: A Direct Projection from Superior Colliculus to Substantia Nigra Pars Compacta in the Cat. Neurosci. 138(1), 221–234 (2006)
11. May, P.J., et al.: Projections from the Superior Colliculus to Substantia Nigra Pars Compacta in a Primate. Soc. Neurosci. Abstr. 450(2) (2005)
12. Redgrave, P., Gurney, K.: The Short Latency Dopamine Signal: A Role in Discovering Novel Actions. Nat. Neurosci. 7, 967–975 (2006)
13. Itti, L., Koch, C.: Computational Modelling of Visual Attention. Nat. Neurosci. 2, 194–203 (2001)
14. Koch, C., Ullman, S.: Shifts in Selective Visual Attention: Towards the Underlying Neural Circuitry. Hum. Neurobiol. 4, 219–227 (1995)
15. Didday, R.L., Arbib, M.A.: Eye Movements and Visual Perception: A Two Visual System Model. Int. J. Man-Machine Studies 7, 547–569 (1975)
16. Lee, D.K., Itti, L., Koch, C., Braun, J.: Attention Activates Winner-Take-All Competition Among Visual Filters. Nat. Neurosci. 2, 375–381 (1999)

17. Deco, G., Rolls, E.T.: Attention, Short-Memory and Action Selection: A Unifying Theory. Prog. Neurobiol. 76, 236–256 (2005)
18. Korsten, N.J.H., Fragopanagos, N., Hartley, M., Taylor, N., Taylor, J.G.: Attention as a Controller. Neural Networks 19, 1408–1421 (2006)
19. Desimone, R., Duncan, J.: Neural Mechanisms of Selective Visual Attention. Ann. Rev. Neurosci. 18, 193–222 (1995)
20. Tsotsos, J.K., Culhane, S., Wai, W., Lai, Y., Davis, N., Nuflo, F.: Modeling Visual Attention via Selective Tuning. Art. Intel. 78(1-2), 507–547 (1995)
21. Itti, L., Koch, C.: A Saliency Based Search Mechanism for Overt and Covert Shifts of Visual Attention. Vision Res. 40, 1489–1506 (2000)
22. Grossberg, S., Raisada, R.D.: Contrast-Sensitive Perceptual Grouping and Object-Based Attention in the Laminar Circuits of Primary Visual Cortex. Vision Res. 40, 1413–1432 (2000)
23. Dommett, E., Coizet, V., Blaha, C.D., Martindale, J., Lefebre, V., Walton, N., Mayhew, J.E., Overton, P.G., Redgrave, P.: How Visual Stimuli Activate Dopaminergic Neurons at Short Latency. Science 307(5714), 1476–9 (2005)
24. Grossberg, S.: Competitive Learning: From Interactive Activation to Adaptive Resonance. Cogn. Sci. 11, 23–63 (1987)
25. Carpenter, G.A., Grossberg, S.: Adaptive Resonance Theory. In: Arbib, M.A. (ed.) The Handbook of Brain Theory and Neural Networks, 2nd edn., pp. 87–90. MIT Press, Cambridge (2003)
26. Reynolds, J.H., Desimone, R.: The Role of Neural Mechanisms of Attention in Solving the Binding Problem. Neuron 24(1), 19–29 (1999)
27. Thrope, S., Fize, D., Marlot, C.: Speed of Processing in the Human Visual System. Nature 381(6582), 520–522 (1996)
28. Thompson, K.G., Bichot, N.P.: A Visual Saliency Map in the Primate Frontal Eye Field. Prog. Brain Res. 147, 251–262 (2005)
29. Hamker, F.H.: The Re-entry hypothesis: The Putative Interaction of the Frontal Eye Field, Ventrolateral Prefrontal Cortex and Areas V4, IT of Attention and Eye Movement. Cereb. Cortex 15, 431–447 (2005)
30. Brown, J.W., Bullock, D., Grossberg, S.: How Laminar Frontal Cortex and Basal Ganglia Circuits Interact to Control Planned and Reactive Saccades. Neural Networks 17, 471–510 (2004)
31. Tsotsos, J.K., Culhane, S.M., Wai, W.Y.K., Lai, Y.H., Davis, N., Nublo, F.: Modelling Visual Attention via Selective Tuning. Artif. Intell. 78(1-2), 506–545 (1995)
32. Tsotsos, J.K., Liu, Y., Martinez-Trujillo, J.C., Pomplun, M., Simine, E., Zhou, K.: Attending to Visual Motion. Comput. Vis. Image Und. 100(1-2), 3–40 (2005)
33. Cutzu, F., Tsotsos, J.K.: The Selective Tuning Model of Attention: Psychophysical Evidence for a Suppressive Annulus Around an Attended Item. Vis. Res. 43(2), 205–219 (2003)
34. Rothenstein, A.L., Tsotsos, J.K.: Attention Links Sensing to Recognition. Image and Vision Computing 26(1), 114–126 (2008)
35. Taylor, J.G.: Race for Consciousness. MIT Press, Cambridge
36. Taylor, J.G., Fragopanagos, N.: Simulations of Attention Control Models in Sensory and Motor Paradigms. In: Proc. Int. J. Conf. Neur. Netw., pp. 298–303 (2003)
37. Taylor, J.G., Rogers, M.: A Control Model of the Movement of Attention. Neural Networks 15, 309–326 (2002)
38. Taylor, J.G.: Paying Attention to Consciousness. TICS 6, 206–210 (2003)