

APPLICATIONS OF VISUAL ATTENTION TO VISION THERAPY & REHABILITATION

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ABSTRACT

Visual attention is a set of tasks with an ubiquitous role in vision and action. It is mediated by large neural networks spanning several areas of the brain. Its two major systems, the anterior and posterior attention networks, are responsible for voluntary and reflexive visual attention, respectively, and may be affected differentially by aging, reading disability, and traumatic brain injury. We review the neurophysiological basis and psychophysical studies of attention, with special emphasis to clinical disorders of visual attention and possibilities for treatment of attentional deficits.

KEY WORDS

aging, anterior visual attention network, attention, development of attention, frontal cortex, magnocellular visual pathway, parietal cortex, parvocellular visual pathway, posterior visual attention network, reading disability, spotlight of attention, vision therapy, visual attention, vision therapy

What Is Attention?

Although there is no single definition for visual attention, a simple way to think of it is as a filter. There is so much visual information bombarding our retinas at any given instant that we simply do not have the neural machinery to process all of it simultaneously. Visual information must be prioritized so that important information gets through, while less critical information is filtered out. Visual attention is actually a broad term that encompasses several basic components, including:

- 1) engaging or activating attention in preparation to detect a target of interest;¹
- 2) directing or orienting attention to a specific location in the field;^{2,3}
- 3) locking attention on that location;⁴
- 4) suppressing irrelevant information from other locations.^{3,5}

In addition, we must at times maintain attention at a given location; either to wait for an expected new stimulus or to completely process all of the current target's visual information.⁶ Finally, we must be able to disengage attention in preparation for processing new information, possibly at another location.^{7,8} Shifting attention from one target to another requires coordination of all of the above components. Each of these processes is, therefore, especially important for reading. Attention is also one of the key mechanisms involved in selection for action, responsible for blocking other possible actions.⁹ Attention has an ubiquitous role in vision. It has been demonstrated to be involved in such diverse visual processes as motion perception,¹⁰ surface perception,¹¹ texture segregation,^{12,13} eye movements^{14,15} and binocular rivalry.¹⁶ Attention also plays a critical role in the planning and execution

of eye movements. Before we can make a saccadic eye movement, visual attention must first be shifted to the intended new fixation point.¹⁴ Conversely, saccadic eye movements can interrupt the effects of attention on cognitive processing.¹⁷

Neurophysiology of Attention

There is now ample evidence for attentional modulation of neurophysiological activity from single-unit recordings. However, the search for the mechanisms of attention has been more elusive. It is thought that selective visual attention is mediated by large networks of neurons rather than individual neurons.¹⁸ Studies of alert and lesioned animals,¹⁹⁻²¹ brain-injured human patients^{4,22} and the recent advent of PET scans^{23,24} have added to our knowledge of the anatomy and physiology of these neural networks.

Posner and colleagues distinguish between three major subnetworks: the posterior attention network, the anterior attention network and the arousal/vigilance network. Each subnetwork subserves a different attentional task. The posterior and anterior attention networks are summarized in Table 1.

Posterior Attention Network

This network is responsible for automatic, reflexive shifting of attention to a novel stimulus, i.e., covert or transient attention. For example, shifting attention, a process that involves disengaging, moving, then re-engaging the focus of attention, requires three neural areas in the posterior attention network to accomplish its task. These are posterior parietal lobe, the superior colliculus and the pulvinar as demonstrated in patients with brain lesions.²⁵ Although its influence is widespread, attention operates "behind the scenes." Posner and Rothbart²⁶ state that the posterior attention network accomplishes its tasks

Table 1. Neurophysiological and clinical differences between the anterior and posterior attention networks

	Posterior Network	Anterior Network
Location	Primarily parietal cortex	Primarily frontal cortex
Functions	Reflexive (transient) attention to novel stimuli (covert orienting) Shifting attention Reflexive eye movements	Voluntary (sustained) attention Decision-making about size of attentional focus and surround
Clinical implications	Visual neglect syndrome	Reduction of attention in dementia
	Both may be involved in the reading task and affected in reading disability	
Possible tasks for rehabilitation	Rapidly-flashed peripheral targets	Fine foveal tasks

without conscious control; it is only the anterior network that provides conscious awareness. It is therefore harder to test its limits via psychophysical measurement than sensory processing.

The parietal lobe is the main cortical area involved in visual attention: there is evidence that damage to the parietal region from strokes or injury severely limits the ability to attend to targets.²⁷⁻²⁹ Patients with posterior parietal cortex (PPC) lesions are unable to accurately locate objects, even though they can identify them.³⁰ In neglect, patients essentially “ignore” the affected hemifield.³¹ This inability to detect targets in the neglected hemifield is not a consequence of impaired sensory processing, but of an attentional deficit.³² This suggests that sensory processing is completed prior to the stage of the lesion. Patients with neglect can engage attention; they cannot disengage and move attention into the neglected hemifield.³³

Visual neglect is more likely with right parietal lesions.^{18,34,35} These lesions are biased to the processing of global object information³⁶ and preparation for action.³⁷ The difficulty in locating objects may be attributed in part to the overall role of the parietal cortex in spatial localization. Here, attention serves as the mediator of the transformation between sensory and motor maps;³⁸ patients with parietal lobe lesions exhibit a shift in the reference point for egocentric localization.³⁹

The superior colliculus may form the link between shifting attention and oculomotor activity.²² This subcortical visual system, involved in reflexive attention, detects novel events.⁴⁰

It is well established that the pulvinar, a thalamic structure neighboring the dLGN,

plays a role in restricting attention to a new locus and filtering out irrelevant locations.²³ Its neurons fire more briskly when attending a target.⁴¹ The pulvinar is reciprocally interconnected with several visual cortical areas,⁴² and exhibits retinotopic organization.^{43,44} Pulvinar neurons have lateral inhibition, sharpening the difference in firing rates between neighboring cells. This is much like lateral inhibition in the retina enhances small differentials in activity arising from lightness differences. LaBerge and co-workers⁴⁵ proposed that lateral inhibition between principal cells of the pulvinar provides a mechanism by which the pulvinar helps to direct the focus of attention onto a target, and filter out distracting information. Simulations of such a pulvinar neural circuit suggest that the pulvinar serves to produce a pronounced concentric focus of attention and surround region similar to that reported by Steinman et al.³

The Anterior Attention Network

This entity is composed of the frontal lobes and anterior cingulate cortex. It is involved in cognitive control of sustained attention,^{46,47} including the determination of the trade-off between how much of the visual field we attend versus how much we ignore. Damage to the frontal lobes affects this balance. This is because the frontal lobes are involved in motor control. Thus, lesions here also yield a neglect that affects motor planning more than sensory vision.³⁵

The posterior and anterior attention networks may be thought of as roughly corresponding to the attentional correlates of the “where” and “what” streams of the visual pathways;^{48,49} the posterior network determines where to direct attention, while

the anterior network controls what is to be attended at that location.

Psychophysical Investigations

Attention can be thought of as a “bottle-neck” that restricts the amount of information reaching cognitive circuits of limited capacity.⁶ According to Broadbent,⁵⁰ the sensory system first processes all basic visual features in the visual field in parallel. However, higher-level mechanisms that interpret, recognize and identify the stimulus may only process one stimulus at a time in a serial fashion. Attention therefore is a selective filter that preferentially allows only some visual information to reach the capacity-limited identification mechanisms and therefore consciousness. The attenuating effects of attention are relative rather than absolute;^{51,52} i.e., unattended information is not totally blocked and can break through to consciousness.

Attentional Focus

Attention is directed to one particular location in the visual field called the attentional focus (or spotlight of attention). It may not necessarily be coincident with the fovea because it can be moved independently of eye movements.^{22,53,54} Within the spotlight, reaction times for detection and discrimination of visual stimuli are faster,⁵⁵⁻⁵⁷ and the visibility of the attended target is increased.⁵⁷ PET scans confirm the effects of attention by exhibiting larger responses when the focus of attention coincides with a visual stimulus than when it does not.²⁴ Conversely, response times are slower for stimuli located in the remaining portions of the visual field^{56,58} and the visibility of stimuli outside of the attentional focus is reduced.⁵⁸ Visual attention therefore serves to prioritize our visual sensory input so that important information is enhanced while relatively irrelevant information is inhibited.⁵⁹

Shifting of Attention

For attention to be focused on a new location, the attentional focus must be shifted across the visual field to that location.⁶⁰ The attentional response builds and ebbs at the first locus, then builds and declines at the second locus. The allocation of visual attention is to a specific location in two-dimensional, rather than three-dimensional visual space.⁶¹ Eriksen and co-workers^{57,62} demonstrated that once the attentional spotlight has been shifted to a particular location, the observer could then “zoom in” to focus on small details in that area. The size of the focus can vary according to task.^{45,63,64} As the size of the

focus shrinks, finer discrimination and increased performance are allowed,⁶² but reaction times are longer. Not surprisingly, the size of the attentional focus increases with retinal eccentricity,⁶⁵ reflecting the larger receptive field size and reduced resolution capability. The neuroimaging study of Müller et al.⁶⁶ provides support for this zoom lens metaphor.

Faster processing time and enhanced detectability are the hallmarks of the focus of attention. However, regions outside of the focus are not left unaffected by visual attention; these portions of the visual field are actually actively inhibited by the attentional process. There is both slower and less efficient processing outside of the attentional focus. Steinman et al.³ were able to directly map out these two major zones of differing attentional response. They found a narrow excitatory region at and near the cued location, in which visual processing is enhanced or accelerated.⁶⁷ This is analogous to the attentional spotlight of earlier theories.⁵⁷ Outside of this is a large inhibitory surround zone in which visual processing is suppressed and slowed down.⁶⁸ The focusing of attention on a particular location, while there is attenuation of activity elsewhere, has been shown to improve detection thresholds within the attentional focus thresholds,⁶⁹ as well as spatial resolution.⁷⁰ Thus, discrimination thresholds are unaffected for the same set of stimuli.⁷¹ Shiu and Pashler⁷² noted similar results in reaction time experiments. Changes in the width of the attentional focus could underlie learning effects in humans during visual search tasks.⁷³

Steinman et al.³ modeled attentional “perceptive fields”^{74,75} using difference of Gaussian functions^{74,76} typically used in neurophysiological studies of neuronal receptive fields. Such functions provided an excellent fit to their attentional enhancement/inhibition plots. This concentric center-surround organization is found in receptive fields throughout the visual system.^{77,78} However, in the case of the attentional perceptive field, the overall field size is very large.³ Its total size more closely matches receptive field diameters of neurons in higher cortical areas such as MT cortex⁷⁸ or inferotemporal (IT) cortex.⁷⁹ Support for the center-surround theory comes from neuroimaging studies that have found excitation in visual processing within striate and extrastriate cortex for stimuli inside the attentional focus,⁸⁰ yet inhibition outside of the attentional focus.⁸¹

The time course of attention remains unchanged regardless of the retinal locus stimulated.⁸² After the onset of a cue, visual performance exhibits a rapid rise to a sharp peak, with a minimum latency of 50 ms.^{3,57,83,84} After reaching its peak, the improvement in performance gradually dissipates until the beneficial effects of attention disappear by 200 to 300 ms.^{3,27,82} A second activation of attention can be seen after 400 ms following the onset of the cue,⁸⁵ reaching a maximum effectiveness at 600 ms, although it can last at least 1800 ms.⁸² The two activations of attention have been called transient attention and sustained attention, respectively, by Nakayama and Mackeben;⁶⁹ others have used the terms reflexive attention or the orienting response^{27,86} versus voluntary attention.⁸⁷ Müller and Rabbitt⁸⁸ postulated that peripheral cues trigger a reflexive attentional system, and central cues a voluntary system, mirroring the “focal” and “ambient” visual systems noted by behavioral optometrists.

Orienting and Transient Visual Attention

The orienting response is an automatic and involuntary focusing of attention towards any sudden change in the visual field.^{1,89} Transient attention is thought to be a bottom-up process as suggested by its retinotopic mapping; i.e., if one moves the eye, the region of the visual field that is enhanced by transient attention moves with the eye and remains at the same locus relative to the retina.²⁷ In addition, the size of the attentional focus scales with retinal eccentricity.⁹⁰ While transient visual attention is dominated by the magnocellular pathway,^{91,92} it does have parvocellular input as well.⁹³ Conversely, sustained attention requires a top-down voluntary cognitive decision about where to locate the attentional focus,^{87,94} which makes it difficult to divide one’s attention. Voluntary attention can be interfered with and overridden by reflexive attention.⁸⁸ Discrimination of fine spatial details requires long processing times, which may partly reflect the involvement of sustained visual attention.^{3,71} This shift from transient to sustained attention has also been demonstrated by a scalp topography of visual evoked potentials consistent with a generator site well outside of striate cortex.⁹⁵

Clinical Implications of Visual Attention

Much of what we know about attention comes from clinical research on patients.

For example, we can understand more about the structural and functional architecture of attention by examining the relationship between development of cortical areas in infancy and the first appearance of the ability to perform specific attentional subtasks. In addition, by knowing how attention develops clinicians can develop a realistic expectation of what visual tasks infants should be capable of at particular ages.

Developmental Aspects

The cerebral cortex of infants exhibits substantial development in terms of richness of synaptic connections after birth. This development does not progress at the same rate in all cortical areas. For example, the cortical visual pathways are not fully developed until a few months of age, with different visual functions reaching adult-like levels at different ages.⁹⁶

Bronson⁹⁷ first suggested that subcortical structures in the retinocollicular pathway dominate the control of visually guided behavior in newborns, with the cerebral cortex playing little role until it has reached a certain level of development. This view has been supported by more recent research suggesting the development of subcortical visual pathways and their cortical connections prior to cortico-cortical connections.⁹⁸ It is not until the magnocellular pathway to the middle temporal cortex has sufficiently developed that infants perceive coherent motion or exhibit pursuit eye movements. At about four months of age, infants make saccades to precued stimulus locations; taken together, these findings suggest that covert attention has developed.⁹⁹ The earlier development of the anterior attention network relative to the posterior network is in agreement with research that suggests that selective attention to global form develops more slowly in children than does attention to local form.¹⁰⁰ With increasing age, infants improve in their ability to shift attention,⁹⁹ but this ability does not reach adult levels even in young childhood.¹⁰¹

Visual Neglect

Lesions in the brain structures subserving attention can lead to profound attentional abnormalities. One of the most pronounced attentional deficits, which arises from posterior parietal lobe damage, is the visual neglect syndrome.^{27,29,30,102} In visual neglect, the patient fails to notice a visual stimulus in a complex or natural environment; neglect is typically restricted to one hemifield. The loss of vision is not the

same as that of a simple visual field loss. Sometimes when a stimulus is presented in the affected hemifield in isolation, it actually will be perceived. However, if stimuli are presented to both hemifields simultaneously, the stimulus in the affected hemifield undergoes what is called extinction – it fails to reach consciousness. In other words, it is the presence of a second stimulus that results in the inability to see the target in question. Extinction is thought to involve mostly sustained, voluntary attention, since instructing the subject to disregard stimuli in the unaffected hemifield reduces the extinction effect.¹⁰³

Aging

Attentional processing may be diminished even in the normal aging population.¹⁰⁴ It has been suggested that only cognitive-based effortful attention is affected;^{105,106} however, transient visual attentional loss in normal aging was confirmed by Steinman et al.¹⁰⁷ who examined aging patients without Alzheimer's disease. It is the magnocellular component of transient visual attention that is degraded in normal aging, with the parvocellular component left unaffected.¹⁰⁷ Attentional deficits in older drivers are associated with increased motor vehicle accident rates.^{108,109} These drivers may not recognize their deficits and therefore do not self-restrict their driving activities.¹¹⁰

Reading

Young individuals can be affected by alterations in visual attention. This is evident in reading disability.¹¹¹⁻¹¹³ In these patients, the attentional focus is excessively constricted, and the inhibitory surround of the attentional perceptual field is more pronounced.¹¹⁴ Such restrictions could hamper the ability to read text by making it more difficult to determine the location of letters. For example, with parietal lobe lesions, patients are unable to read (acquired dyslexia) due to problems locating letters within words.¹¹⁵ Bilateral damage to the parietal lobes, sometimes seen in autistic patients, also results in a narrowed focus of attention.¹¹⁶ In addition, the activation of transient visual attention decays more rapidly in reading disabled subjects than in normal readers, with a prolonged period of profound inhibition of sustained attention, thereby preventing the disabled reader from fully processing the fixated text.¹¹⁴ This may simply be an exaggeration of the normal "psychological refractory period", also called inhibition of return, which prevents attention from

lingering at one location for too long.^{27,117} Lavie¹¹⁸ notes that the attentional spotlight is narrower with a larger perceptual load; perhaps an overload of perceptual information for the reading disabled subject contributes to the narrowing of their attentional focus.

Optometric Clinical Application

Despite decades of research and clinical findings, we still know very little about the mechanisms of attention. However, we do know that attention plays a large role in the processing of form and the recognition of objects, and that attention must be activated in order to fully process visual information. We therefore must find ways to ensure that visual attention is engaged when asking our patients to perform challenging visual tasks, such as those used in vision therapy or when reading.

More importantly, we know that attention can be affected by disease processes in our patients. Recent studies have demonstrated that attention can be trained.¹¹⁹ Training has been demonstrated to have pronounced effects on visual search tasks involving the allocation of visual attention.^{73,120} This opens up the possibility of treating visual attentional disorders in patients. It is optometry's responsibility as the primary care profession dealing with visual function and efficiency to help develop sensitive new clinical tests for early visual attention disorders and rehabilitative techniques to improve the visual function of these patients. Mainstream optometric examinations focus only on low-level visual processing, such as light detection, contrast detection, resolution and color discrimination. As we have seen in this article, profound visual losses can occur even when these capabilities are normal. Optometry must also encompass the detection and treatment of high-level visual disorders requiring attention, object recognition, memory, and planning for motor action.

Such clinical optometric techniques do not yet exist, but a knowledge of visual attention^{121,122} allows one to speculate on what they could be. For example, the amplitude of the visual evoked potential is directly related to the strength of sustained visual attention. By using similar evoked potential recording techniques as the sweep VEP used to rapidly test infant vision, we could continuously monitor VEP amplitude, and produce a tone whose pitch is related to the amplitude, and therefore the strength of attention, at any given mo-

ment. This could provide a biofeedback technique for training attention.

Many vision therapy tasks for the treatment of amblyopia require attention to fine details, such as dotting the center of letter O's on printed pages. Perhaps part of the effect that vision therapy has on amblyopia is because sustained visual attention "primes" the visual system, making it more amenable to enhancement through training. Transient visual attention, processed primarily through the magnocellular pathways, would require different stimulation for maximal activation. Most current vision therapy tasks don't specifically target the magnocellular-pathway; the slow, central, focused tasks that are commonly used activate the parvocellular-pathway and sustained attention instead. To address therapy of transient attention, the use of flashing or moving stimuli might better "prime" the visual system for learning. For example, the Wayne saccadic fixator^a might tap transient attention because it can present stimuli that suddenly appear in random positions in the visual field. Other peripheral awareness tasks, if presented with rapidly-flashed targets, might also serve to trigger transient attention. The reading task involves the activation of both transient and sustained visual attention. Tasks incorporating both fine detail and changing stimulation might help those with reading disability. Perhaps this is part of the reason why reading eye movement therapy tasks may be helpful in the improvement of reading scores in dyslexic subjects.^{123,124}

Summary

The study of visual attention and other cognitive aspects of vision is still in its infancy, but there has been a flourish of scientific research in the past ten years. It is only a matter of time before health care professions and therefore the public become more aware of visual cognitive disorders. It is in the area of higher-order visual processing that optometry can play a large role in shaping vision care of the future.

This article is a shorter version of: Steinman SD, Steinman BA. Visual Attention: Basic & Clinical Aspects. In: Super S, ed. Intention, Attention, Inattention and Neglect. Santa Ana, CA: Optometric Extension Program Foundation, Inc., 2006.

The authors have no financial interest in the Wayne Saccadic Fixator.

Source

- a. Wayne Engineering, 8242 N. Christiana Avenue, Skokie, IL 60076

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 Date accepted for publication:
 July 31, 2007