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Aging and Vision: Changes in Function and Performance from Optics to Perception

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Abstract

Age-related declines in vision can have a major impact on the health and well-being of an older population. A review of research on aging and vision indicate that these declines occur at multiple levels of the visual system including optics, sensory processing, and perceptual processing, and are not likely to be due to a systemic change in brain function (e.g., generalized slowing; common cause hypothesis) as a result of normal aging. In addition, declines in sensory and perceptual processing are not due to low-level explanations such as the amount of light that reaches the retina. Declines in visual performance are due to a variety of distinct factors that include spatial integration and difficulty in processing visual information in the presence of noise. Neurophysiological studies suggest that processing declines may be due in part to changes in cortical inhibition mediated by changes in the level of neurotransmitters associated with inhibition. Despite the widespread declines in function with normal aging recent research suggests that perceptual learning can be used to dramatically improve visual function for older individuals. This research suggests a high degree of plasticity of the visual system among older populations and suggests that perceptual learning is an important tool for the recovery of age-related declines in vision.

Introduction

An important and well documented finding in the literature is that perceptual and cognitive systems change with age. These changes can have a profound impact on the quality of life, health and wellbeing of an older population---individuals age 65 or older. Age-related changes in visual function have been implicated as a major contributing factor in the incidence of falls among the elderly¹ as well as the increased accident risk for older drivers^{2–6}. Several studies have shown that age-related changes in vision led to significant quality of life changes because of decreased mobility^{7–9}. In this article I will provide a general overview of what is known regarding the effects of normal aging (processing changes independent of age-related diseases such as Alzheimer's disease or macular degeneration). For the sake of convenience, age-related declines in vision can be categorized into three general levels---changes in the optics of the aging eye, sensory changes (from retina to early visual cortex), and perceptual changes (mid and high level visual cortex). The present review will discuss the impact of aging for these levels but, for the purpose of brevity, will not include a review of visual cognition issues such as attention or visual working memory. The reader is referred to other publications for excellent discussions of these issues.^{10,11}

[ARE EFFECTS OF NORMAL AGING A MOLAR SYSTEMIC CHANGE IN THE BRAIN?]

Before reviewing the research on aging and vision an important issue is whether age-related declines in vision are associated with molar changes in brain function (that occur throughout

the older brain) and processing that occur with normal aging. For example, research has proposed that age-related declines in cognition are due to generalized slowing.¹² Other studies have proposed a common cause hypothesis for cognitive/sensory declines due to aging.¹³ However, theories such as generalized slowing or the common cause hypothesis, while useful in explaining declines in cognition, are not useful as a theory to account for all aspects of age-related declines throughout the brain. Consider, for example, the evidence on age-related structural changes in the brain. Studies of age-related changes in white matter volume indicate strong evidence of declines in areas such as prefrontal cortex and hippocampus but no significant changes in visual cortex.¹⁴ This finding suggests that age-related declines in brain function do not occur equally in all brain regions and that the type of structural cortical changes that are associated with declines in cognitive performance do not occur in visual cortex. In addition, there is no decrease in neural density in visual cortex as a function of age¹⁵ and no clear evidence of changes in neuronal morphology (i.e., degenerating dendrites, myelinated axons or axon terminals).¹⁶ Evidence does exist of some age related changes in dendritic measures (i.e., length, density) in area 18 of human cortex. However these measurements were relatively stable after age 40 suggesting that dendritic/spine degeneration may not be an outcome of normal aging.¹⁷ Instead, evidence of age-related changes in visual cortex is primarily associated with functional aspects of neurons and neuronal communication in the visual system. For example, electrophysiological studies have found elevated baseline firing rates in senescent animals and broader tuning curves of single cell responses to orientation,^{18–20} age-related degeneration in intracortical inhibition in V1,^{19,21} and age-related declines in temporal processing speed in areas 17 and 18.²² These electrophysiological changes have been associated with changes in inhibition, possibly due to reduced levels of GABA^{18–20,23} or acetylcholine (ACh) in early levels of visual cortex.²⁴ These results, considered together, suggest that age-related declines in vision are primarily due to functional, not structural, changes in brain function associated with normal aging.

[AGE-RELATED CHANGES IN OPTICS]

The first level of vision in which age-related changes occur is the projection of light to the retina (optics). For example, studies have found age-related changes in biochemistry of the cornea and corneal thickness, lens opacity, vitreous humor, accommodative focus and optical focus due to myopia, hyperopia and astigmatism. A thorough review of this literature is beyond the scope of the present article. However, the reader is referred to several excellent reviews of these issues.^{25–27} Although changes in the optics of the eye in elderly individuals can lead to a reduction in light that reaches the retina (i.e. retinal illuminance) it is clear that these age-related changes cannot account for age-related declines in sensory and perceptual performance. This is because age-related changes in optics alter the input to visual cortex and should have a uniform effect on visual processing. For example, reduced light due to lens opacity can alter the ability to detect an impending collision with an approaching object, but the impact on the ability to detect a collision should be constant across all speeds and directions. Thus, although one might find an overall effect of age it will not vary with parameters associated with motion processing (i.e., speed and direction). However, a review of the literature clearly indicates that many age-related declines in sensory and perceptual performance are selective and not constant.

[AGE-RELATED CHANGES IN SENSORY PROCESSING]

The second level of age-related changes in vision concerns the neural systems responsible for processing sensory information. These changes include spatial and temporal changes in the neural mechanisms from the retina to early levels of visual cortex and involve the detection and discrimination of simple features such as luminance patterns, orientation,

contrast, and motion---the building blocks of higher-level visual processing. For example, studies have found age-related changes in spatial and temporal properties of rods,²⁸ cones,²⁹ and retinal ganglion cells.³⁰ In addition, studies have found declines in the number of rods in parafoveal vision³¹ and the number of neurons in the ganglion cell layer of the retina.³²

Several excellent reviews have been published documenting age-related changes in sensory processing^{25,27} and the reader is referred to these excellent sources for a detailed discussion. However, a brief review of some of the major findings is appropriate as these results bear directly on understanding age related declines in higher level aspects of visual processing.

[Luminance, Contrast, and Spatial Orientation]

It is well documented in the literature that sensitivity to luminance and variations in luminance or contrast declines with age and that these changes can impact higher-level perceptual processing such as object detection.³³ Research has shown decreased sensitivity to luminance, particularly under low levels of luminance or scotopic vision.^{34,35} These declines have a direct impact on the ability of older observers to perceive spatial changes in luminance or contrast and are usually assessed in studies of orientation discrimination. Research on age-related declines in orientation has examined sensitivity to detect sine-wave grating patterns (spatially-modulated luminance patterns according to a sine function) or Gabor patches (sine wave gratings in which contrast is decreased from the center of the patch outwards according to a Gaussian distribution). Research with sine wave gratings have shown a steady decrease in sensitivity starting at age 30 and continuing well into advanced age (80 year old participants).³⁶ The decline in sensitivity is not uniform across all spatial frequencies. Sensitivity to low spatial frequencies (less than 2 cycles/deg) is preserved with age. However, sensitivity declines consistently with age for mid to high frequencies (up to 16 cycles/deg). The finding that performance does not decline systematically across all spatial frequencies suggests that age-related declines cannot be due to optical factors such as retinal illuminance (the amount of light cast on the retina). More recent research³⁷ examined sensitivity to discriminate the orientation of Gabor patches when embedded within contrast noise. The results indicated elevated thresholds for older observers when the noise was low. Similar performance was observed for both age groups when the noise was high. In addition, a reduction in luminance for younger observers (and thus a reduction in retinal illuminance) did not result in performance similar to older observers, suggesting that age-related declines in orientation discrimination cannot be accounted for by changes in retinal illuminance. The results of these studies, considered together, suggest that age-related declines in discriminating orientation are dependent on the stimulus characteristics (i.e., spatial frequency, amount of noise) present in the display.

[Motion Perception]

In one of the earliest studies on motion perception and aging³⁸ research examined motion sensitivity (identifying the direction of motion of moving dots presented with noise) for individuals ranging in age from 25 to 80. The results indicated a steady decline in motion thresholds with increased age. Indeed, thresholds for subjects over age 70 were twice that of 30 year old participants. Other research³⁹ found similar results however motion thresholds were significantly higher for older women as compared to older men. This gender effect has been replicated⁴⁰ and there has been no theory proposed to account for this finding. Age-related declines in motion sensitivity have also been found for motion presented in the retinal periphery and have been shown to be independent of changes in acuity with retinal eccentricity.⁴¹ Research has also used random dot cinematograms (random dots moving in a coherent direction but each dot motion path was slightly altered) to examine motion sensitivity and used a multichannel model to assess what characteristics of the visual system might change with age and account for declines in motion processing.⁴² The results of the

model suggested that the age-related declines in performance were due to the motion channels responding to a broad range of motion directions (i.e., less motion selectivity) and increased additive internal noise in the visual system. These results suggest that the tuning of motion sensitive cells as well as the magnitude of background neural noise (baseline firing rates of cells) might account for the age-related declines in visual performance (a similar study has found evidence of changes in neuromodulation and neuronal noise which may account for age-related cognitive declines⁴³). Finally, research⁴⁴ examining spatial suppression and motion perception has found evidence that age-related declines in motion processing may be due to a reduction in center-surround suppression. These results are consistent the results of animal studies^{18–20,23,24} that found a decline in inhibition in visual cortex of older organisms.

[AGE-RELATED CHANGES IN PERCEPTUAL PROCESSING]

The next level in the visual processing hierarchy is the combination of low levels sensory features for the performance of visual tasks such as the perception of 2D form, depth, and scene layout, and optic flow analyses for locomotion and collision avoidance. Age-related changes in perceptual processing reflect changes that occur at mid or high levels of visual processing and include cortical regions such as V3A, MT+, LO and higher visual areas. Similar to the results of optical and sensory levels the evidence of age-related declines in perceptual processing cannot be characterized by a single underlying factor. Instead, the types of processing declines associated with normal aging are highly idiosyncratic and specific to the types of processing critical for a particular visual task.

[Form Perception]

Research on aging and 2D form perception has examined the ability of observers to spatially integrate features to perceive contours and form.⁴⁵ In one study subjects were shown pattern of Gabor patches that formed a “C” contour and were asked to identify the location of the gap in the contour. Performance for younger subjects improved when the Gabor patches were aligned with the contour as compared to varied in orientation. In contrast, older subjects did not improve under these conditions. Similar age-related declines in spatial integration have been found in studies examining contour boundaries defined by kinetic occlusion—the accretion and deletion of background texture by a moving opaque foreground object.⁴⁶ By systematically varying the speed of motion and the dot density the contribution of spatial and temporal integration to age-related declines in vision was assessed. The results indicated a greater decrease in performance for older observers, as compared to younger observers, with changes in dot density. Both groups showed a similar effect for speed changes. These results suggest that age-related declines in extracting contours and form are due to declines in spatial but not temporal integration.

[Depth, Slant and 3D Shape Perception]

Research on the perception of depth, slant and 3D shape indicates that the performance of older individuals does not decline across all conditions but is based on specific aspects of processing needed to perform the task. For example, studies on detecting 3D shape from motion parallax⁴⁰ indicate that older observers have difficulty detecting surfaces at low texture density levels (most likely due to a decline in the ability to spatially integrate the velocities to perceive the 3D shape) and when random noise is present. However, detecting coherent 2D motion was not predictive of age-related declines in detecting 3D surfaces. In addition, studies have shown that age-related decrements in global 2D motion perception are not predictive of age-related decrements in detecting or discriminating optical flow components.^{41,47} These findings suggest that declines in higher level motion processing are not due to declines in low level motion processing. Research examining depth and shape

perception from motion parallax⁴⁸ indicate that although age-related declines in shape perception and discrimination were quite large the ability to judge the depth of the same patterns did not decline with age. So what might account for these results? The perception of depth requires the observer to determine and use the maximum and minimum velocities of the display (essentially 2 points). The perception of shape (with the exception of planar surfaces) requires observers to integrate information over locally varying velocities of 3 or more points. Thus, performance decrements in 3D shape perception, for older individuals, are likely due to declines in spatial integration. This general finding is not specific to the use of motion parallax information. Studies examining stereopsis have found that judging the depth order of stereoscopically defined points shows little decline with age but judging shape from stereopsis does show a decrease in performance particularly for large disparity values.⁴⁹

Research on age-related differences in slant perception from texture, motion parallax and binocular disparity indicate that for a wide range of surface slants there is little or no difference in performance between older and younger observers.⁵⁰ However, older subjects did have a higher degree of variability in their judgments. This finding of similar performance for older and younger observers for the perception of slant is likely due to the same processing decline observed with 2D motion and optic flow and with depth and shape perception. Specifically, age-related declines in performance are dependent on order of the spatial derivative of the information source. To determine slant the visual system must use first order (first spatial derivative) information. In contrast to determine 3D form or shape the visual system must use second order (second spatial derivative) information. Thus, the age-related declines observed in form and shape perception are likely the results of difficulty in using higher order spatial information.

This conclusion might lead one to assume that similar effects should occur for other higher level motion stimuli that involve form---such as the perception of biological motion. However, research on aging and biological motion has shown that, in general, the performance of older individuals is quite similar to the performance of younger individuals.^{51,52} Performance does decline for older observers when noise is present in the stimuli.⁵² This finding is consistent with the findings of other studies, discussed earlier, that found age-related declines in the perception of 2D motion or shape perception from motion parallax when noise was present. So what might account for the results of biological motion? Previous research has proposed that the computational analysis of biological motion is based on the rigidity of pairs of points in biological motion.⁵³ The use of pairwise rigidity is thus similar to the recovery of local depth (i.e. is based on two points), and thus does not involve the use of higher order spatial derivatives as is required for 3D shape recovery.

[Layout and Scene Perception]

An important issue for many high-level visual tasks, including navigation and obstacle avoidance, is the recovery of layout information and the organization of scenes. Previous research has shown that the ground surface is an important organizing factor for the perception of layout in scenes. Research on age-related differences in the use of ground surfaces for determining scene layout has shown a decreased use of the ground surface in organizing scene layout.⁵⁴ The decreased reliance of ground surface information by older observers for perceived spatial layout (and the location of potential obstacles in the visual world) may be a contributing factor in the increased rate of falls among the elderly.

[Optical Flow]

Finally, a last category of information for mid to high level visual processing that has not been discussed in detail is optical flow. Optical flow is useful for locomoting in the

environment and for detecting and avoiding impending collisions. Research on the age-related differences in the perception of heading (the direction of locomotion) has found a small but consistent decline in the ability of older observers to determine the path of locomotion.⁵⁵ These effects were not due to the number of dots in the flow field suggesting a general decline in the use of optical flow information. This conclusion was confirmed by studies examining sensitivity to different components of optical flow information in central vision.⁴¹

Unlike the general age-related declines in judging the direction of locomotion, research on age-related differences in detecting an impending collision with the observer indicates that there are selective age-related declines in processing. Studies have examined the ability of older and younger observers to detect collisions on linear paths at constant velocity⁴ and on linear paths during deceleration or braking.⁵⁶ A consistent finding in both types of studies is that at slow speeds older individuals perform as well as younger observers. However, at higher speeds older observers, as compared to younger observers, show a decline in the ability to detect a collision independent of changes in response bias. Indeed, at the highest speed examined (60 mph) older observers required an additional 2.5 sec of viewing the trajectory in order to have performance comparable to younger observers. This additional viewing time suggests that older individuals may not have adequate time to initiate and complete a control response to avoid an impending collision. Collision events for objects moving on linear paths at constant speed are defined by two sources of visual information – expansion and a constant bearing (location in the visual field) of the approaching object. The increased time needed at higher speeds suggests that older observers have difficulty recovering these critical information sources when the observer is moving. The decreased ability to detect an impending collision is likely to be an important factor in the increased crash risk among older drivers.^{2,5}

[PERCEPTUAL LEARNING AND PLASTICITY OF THE AGING VISUAL SYSTEM]

Previous research has demonstrated that experience and training can be used to improve cognitive performance among older individuals.^{57,58} Given the wide range of age-related declines in vision and visual processing an important issue is whether any method or procedure can be used to improve visual function. An extensive literature with college-age participants suggests that perceptual learning (PL)—repeated exposure or training with stimuli—can improve performance for visual tasks such as discriminating texture, motion, or orientation (see Ref. 59 for a detailed review). Previous research has shown that practice in a divided attention task can result in improved performance for older individuals.⁶⁰ In addition, practice has been shown to improve the speed and accuracy of responses by older individuals in letter identification and brightness judgments.⁶¹ Recent research⁶² has examined whether PL can be used to improve visual performance for older individuals and examined whether these changes may be due to improved processing in early levels of visual cortex. Subjects were asked to perform a centrally located letter discrimination task (to control for eye fixation) and a peripherally located texture discrimination task presented in a field of noise elements. A mask was presented after the presentation of the stimuli and the time between the onset of the stimuli and onset of the mask was varied (stimulus onset asynchrony or SOA). A SOA threshold was derived for each subject as the SOA at which 66% accuracy was obtained for the texture discrimination task. Performance for the central task was near optimal levels (greater than 95%). Older participants received two days of training that was based on incremental levels of difficulty specific to each subject's threshold. The results indicated a significant improvement in texture discrimination performance that was equivalent to the performance of college-age subjects who did not receive training. The effects of training were maintained when assessed 3 months following

training. An older control group that was presented the same number of trials but with easy stimuli (well above threshold) showed minimal improvement. In two follow up studies they also found that the improved performance was not due to changes in divided attention and was specific to the region in the visual field where the stimuli were presented---suggesting that the improved performance was consistent with changes in early levels of visual processing.

Other studies on aging and PL have examined training with motion stimuli and used the perceptual template model⁶³ to assess what aspects of processing change as a result of PL.⁶⁴ According to the perceptual template model, improved performance could be due to changes in additive noise in the system, multiplicative noise in the system or changes in external noise exclusion (i.e., filtering a noisy input). Subjects were trained over several days with near threshold stimuli. Older and younger subjects were trained with either a drifting sine wave grating or random dot cinematogram. The results indicated improved performance with both motion types for both older and younger subjects. In addition, evidence of transfer to the untrained motion type was found when training with either motion type. Both age groups showed evidence of changes in external noise exclusion. However older subjects also showed changes in internal additive noise. Neither group showed a change in multiplicative noise. If the physiological basis of internal noise is caused by increases in the firing rate of neurons in visual cortex, then it is possible that PL might reduce the increased rate of background activity found in older organisms. An important issue for future research will be to examine this possibility.

[CONCLUSIONS]

In the present review article I have discussed the factors underlying age-related declines in vision. A review of the neurophysiological literature suggests that the changes seen in cortical regions associated with cognition (e.g., dorsal lateral prefrontal cortex and hippocampus) are different from the changes seen in visual cortex. This finding suggests that there is not a single factor that results in age-related declines in performance for all aspects of cognitive and sensory processing. The review has included a discussion of age-related changes in the optics, sensory and perceptual levels of the visual system and how these changes can impact visual performance. The results of this research indicate that the factors that underlie age-related changes in vision are complex and vary according to the type and level of processing. In addition, changes in the early levels of the visual hierarchy (such as the sensory level) are not predictive of changes in higher levels of perceptual processing. Thus, unlike age-related changes in cognition---in which generalized slowing¹² or the common cause hypothesis¹³ has been proposed as a possible mechanism to account for age effects---there does not appear to be a broad underlying factor behind age-related declines in vision. Finally, research on PL suggests that the visual system maintains a high degree of plasticity with age and that training interventions can be used to improve the visual function, health and wellbeing of an older population.

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