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# Larger effect of aging on the perception of higher-order stimuli

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#### Abstract

Widespread deficits are known to accompany normal aging. Contrast thresholds of older and younger observers were measured for static and drifting gratings defined by luminance (first-order) or by contrast (second-order), and for a temporally segmented second-order motion stimulus. Results showed that older individuals had a larger threshold elevation for the perception of second-order stimuli than for the perception of first-order stimuli. This suggests a dissociation between the mechanisms underlying the perception of first and second-order stimuli, and demonstrates that aging may affect the more numerous processing steps required for the analysis of higher level stimuli. © 2000 Elsevier Science Ltd. All rights reserved.

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#### 1. Introduction

Several visual perception deficits present in the healthy elderly cannot be entirely accounted for by the aging optics (Weale, 1982, for a review see Spear, 1993). In addition, the aging brain undergoes non-specific physiological changes. The purpose of this work is to link the effect of changes in the aging brain to visual perception by using static and dynamic stimuli that are assumed to require various levels of cortical processing.

The study of visual perception in the elderly has concentrated on stimuli that are analyzed by the early linear filters of the visual system. Such work includes the study of the perception of spatiotemporally modulated sinusoidal gratings. Studies using drifting gratings have shown that despite equal spatial contrast sensitivity functions for older and younger observers at 1 cpd, older individuals were slightly less sensitive to a 1 cpd grating drifting at slow and medium speeds (Kline, 1987) and at medium speed only (Owsley, Sekuler & Siemsen, 1983). Other studies, using counter-phasing gratings, have found no effect of age at these temporal frequencies for the same spatial frequency (Lundh, Lennerstrand & Derefeldt, 1983; Tulunay-Keesey, Ver Hoeve & Terkla-McGrane, 1988; Elliott, Whitaker & MacVeigh, 1990). Some experiments on the visual perception of the elderly have used more complex stimuli such as random dot displays and have found that older adults had higher percent coherence thresholds (Trick & Silverman, 1991) and higher direction discrimination thresholds (Ball & Sekuler, 1986) than younger adults. A consideration of the changes that the aging brain undergoes becomes helpful in understanding the mechanisms underlying such decreases in sensitivity.

Weale (1975) has suggested that visual perception deficits (beyond optical changes) in the elderly are a result of diffuse cell death in the aged brain. Recent evidence is in agreement with Weale's argument that such cortical changes are widespread and non-specific, but points towards a loss of cellular function rather than a loss of cell number. Indeed, evidence from neuronal counts has shown that cell number is minimally changed in the aging cortex (Rapp & Gallagher, 1996; Morrison & Hof, 1997). In a thorough review of visual deficits in the elderly, Spear (1993) compared evidence from anatomy, physiology and psychophysics, and concluded that loss of cellular function rather than cellular reduction leads to the non-specific impairments observed. Possible mechanisms for deficits that accompany aging come from physiological studies that have found a decrease in neocortical presynaptic boutons in the rat (Wong, Campbell, Ribiero-da-Silva & Cuello, 1998), changes in physiological properties of hippocam-

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pal cells in the monkey (Gazzaley, Thakker, Hof & Morrison, 1997), a decrease of interaction at the cellular level (Rubin, 1997), and a degeneration of the sheath of myelinated axons in the monkey (Vincent, Peters & Tigges, 1989; Peters, Rosene, Moss, Kemper, Abraham, Tigges, et al., 1996). The effects of these physiological changes on behaviour may be observed by comparing various levels of cortical analysis such as those involved in the perception of simple and complex visual stimuli.

First- and second-order stimuli are types of simple and complex stimuli, respectively. First-order stimuli (simple, Fourier or linear) are defined by luminance, while second-order stimuli (complex, non-Fourier, or non-linear) are defined by contrast, texture, or depth (Chubb & Sperling, 1988; Cavanagh & Mather, 1989). Psychophysical and physiological evidence, along with computational modeling suggest that two separate cortical mechanisms underlie the initial processing of firstorder and second-order stimuli (Wilson, Ferrerra & Yo, 1992; Ledgeway & Smith, 1994; Mareschal & Baker, 1998a,b; Wilson, 1998). Wilson and colleagues (1992, 1998) have proposed that the Fourier and non-Fourier mechanisms work in parallel from V1 to area MT (for motion analysis) or V4 (for form analysis), and that non-Fourier analysis requires an additional processing step where rectification occurs (Shapley & Gordon, 1985; Chubb & Sperling, 1988; Sutter, Beck & Graham, 1989; Turano & Pantle, 1989; Victor & Conte, 1991; Wilson et al., 1992). In accordance, a recent fMRI study of first- and second-order motion processing in the visual cortex has shown that first-order motion activation first appears in V1, while second-order motion activation first arises in V3 and VP, and that both types of motion are further analyzed by MT (Smith, Greenlee, Singh, Kraemer & Hennig, 1998).

The goal of the present study is to clarify the processes underlying perceptual deficits in the elderly by evaluating the effect of aging on the sensitivity to stationary and moving first- and second-order gratings. As previously discussed, the aging cortex seems to have a diffuse loss of function. It is thought that the number of steps required for cortical analysis of second-order stimuli are more numerous than those for the analysis of first-order stimuli, and a larger threshold elevation in the perception of second-order stimuli is thus expected in the elderly. In addition the level of processing difficulty is increased with the use of a temporally segmented second-order motion stimulus. ISIs are introduced in the presentation of this stimulus, and its processing is assumed to be more complex than that of a smoothly drifting second-order stimulus, in that the last position of the drifting grating would have to be stored for later comparison, during the ISI. A first control condition is conducted to account for decreased retinal illumination in the elderly, which may affect

thresholds. Because noise is an integral part of the second-order stimulus, a second control condition is carried out to account for the decreased contrast sensitivity function of older individuals at higher spatial frequencies (Owsley et al., 1983).

# 2. First-order, second-order and temporally segmented second-order conditions

# 2.1. Methods

# 2.1.1. Observers

Nine older observers (mean age 69.7 + 4.42 years, range 64-79 years old) and nine younger observers (mean age 23 + 1.58 years, range 21-26 years old) participated in this study. Older observers underwent complete eye exams (refraction, ophthalmoscopy, biomicroscopy, tonometry, stereoscopy), had healthy eyes, and were corrected for the viewing distance. Individuals in the older group had a visual acuity of 20/25 or better and those in the younger group of 20/20 or better. All the observers had normal color vision as established by the H-R-R pseudoisochromatic plates test. Pupil sizes were measured under the experimental conditions and were found to be between 4 and 5 mm in diameter (mean pupil size 4.44 + 0.496 mm) for the older observers, and between 5 and 7 mm in diameter (mean pupil size 6.43 + 0.787 mm) for the younger observers. In addition, eight of the nine older observers and only six of the nine younger observers were psychophysically experienced.

# 2.1.2. Apparatus and stimuli

Stimuli were generated by a Power Macintosh 6100/66AV and displayed on an Apple high resolution 15 inch color monitor. The monitor had a refresh rate of 67 Hz, a resolution of  $640 \times 480$  pixels, and the viewing distance was 1.71 m.

The stimuli were circular hard-edged patches subtending a visual angle of 4° in diameter, each noise element subtended 2.2 arcmin, and mean luminance was 10.8  $cd/m^2$ . The blue and green guns were set to a minimum and the red gun was at a maximum, yielding u' and v' values of 0.4100 and 0.5210, respectively. The monitor was calibrated so that the contrasts were linearized. The stimuli were presented for 750 ms and the sine wave was drifted at 2, 4, or 8 cycles/s (Hz) for the motion stimuli and was static (0 Hz) in the static condition. A red stimulus was used because the absorption of wavelengths beyond 600 nm by the yellowed aging lens is similar to that of younger lenses (Weale, 1963). The spectral components of the screen are characterized by a sharp peak at 620 nm that is not filtered by the optics of the eye (Faubert, 1994; Faubert, Diaconu, Ptito & Ptito, 1999). Stimuli were made and

presented using the PIXX<sup>©</sup> software and were based on those introduced by Ledgeway and Smith (1994).

2.1.2.1. First-order stimulus (Fig. 1a). The first-order stimulus consisted of luminance-defined 1 cpd sinemodulated (envelope) static grey-scale noise (carrier), where the envelope and carrier are added. The luminance profile at point (x, y) is defined as:

L(x, y)

$$= L_{\text{mean}} \{ [1 + m_{\text{env}} \cdot \sin 2\pi x f] + [1 + 0.5 \ m_{\text{car}} \cdot R(x, y)] \}$$

where  $L_{\text{mean}}$  is the mean luminance of the display,  $m_{\text{env}}$ and f are the modulation depth and spatial frequency of the envelope, respectively, and  $m_{\text{car}}$  is the contrast of the carrier. R(x, y) is the static noise carrier consisting of dots whose individual luminances were randomly assigned as a function of  $\sin(x)$ , where (x) ranged from 0 to  $2\pi$ . Noise elements in grey-scale noise as opposed to those in binary noise are randomly assigned various intensity levels along a sine function rather than black or white polarities. The amplitude of the luminance modulation (Michelson contrast) varied between 0 and 0.55, and the mean contrast or modulation depth was defined as:

Modulation depth =  $(L_{\text{max}} - L_{\text{min}})/(L_{\text{max}} + L_{\text{min}})$ 

where  $L_{\text{max}}$  is the maximum luminance and  $L_{\text{min}}$  is the minimum luminance averaged over adjacent noise elements.

2.1.2.2. Second-order stimulus (Fig. 1b). The second-order stimulus consisted of contrast-defined 1 cpd sinemodulated static grey-scale noise, where the envelope and the carrier are multiplied. The luminance profile of the second-order stimulus at point (x,y) is defined as follows:

$$L(x, y) = L_{\text{mean}} \{ [1 + m_{\text{env}} \cdot \sin 2\pi x f] [1 + 0.5 \ m_{\text{car}} \cdot R(x, y)] \}$$
  
where the terms are the same as those described

where the terms are the same as those described for first-order stimuli but the envelope and carrier are multiplied rather than added. The amplitude of the contrast modulation was varied between 0 and 1, and the mean contrast or modulation depth was defined as:

Modulation depth = 
$$(L_{\text{max}} - L_{\text{min}})/(L_{\text{max}} + L_{\text{min}})$$

where  $L_{\text{max}}$  is the maximum and  $L_{\text{min}}$  is the minimum luminance of neighboring noise elements in the high contrast areas of the stimulus. In other words, the contrast between adjacent noise elements of opposite polarity was modulated across the stimulus between 0 and a maximum value.

2.1.2.3. Temporally segmented second-order motion stimulus. This stimulus consisted of a drifting second-order stimulus as described above, in which a 60 ms ISI was introduced every 45 ms. The stimulus disappeared during the ISI while the background remained, and reappeared in the position it was in, before disappearing. The level of difficulty in this task is assumed to be higher than that of the second-order motion task because the position of the sine wave must be stored during the ISI for comparison to a subsequent event. This comparison allows for drift direction to be assessed. Total presentation time was 750 ms and drift speed of the sine wave was 2 Hz for a 1 cpd grating.

a. b.

Fig. 1. Stimuli used in this experiment. (a) First-order or luminance-defined grating. (b) Second-order or contrast defined grating. The stimuli used in the experiment were red rather than grey.



Fig. 2. Mean contrast thresholds expressed in modulation depth as a function of drift speed on a logarithmic scale. Results are shown for older (full symbols) and younger groups (empty symbols) for first-order (squares), for second-order (circles) and for the segmented second-order motion (triangles) stimuli. (A) Thresholds for the orientation task in the static condition are on the left-hand side of the figure, and those for the three drift speeds (2, 4 and 8 Hz) on the right-hand side of the figure. (B) Thresholds for the direction of motion discrimination task at the three drift speeds. The bars represent the standard error of the mean and are smaller than the symbols where they are not visible.

Other drift speeds were not tested in this condition because the perception of motion direction became ambiguous.

#### 2.1.3. Procedure

The minimum contrast necessary (as defined by a 75% correct threshold criterion) to discriminate the orientation (vertical or horizontal) of first- and second-order static gratings was established for the static condition. The minimum contrast necessary to discriminate the orientation (vertical or horizontal) and the direction of motion (left ward or right ward) of first- and second-order drifting gratings was established at various drift speeds for the moving condition. Thresholds were measured using the PEST method (Pentland, 1980). The order of test conditions was randomized across subjects. Viewing was binocular.

# 2.2. Results

#### 2.2.1. Orientation task

Results (Fig. 2A; Table 1a) show that thresholds for the perception of first-order stimuli are higher for the older group than for the younger group by a factor of approximately 1.5 for the drifting condition only. The older group shows a 2-fold threshold elevation for stationary and drifting second-order conditions. Separate ANOVAs were conducted for the static and drifting results. A first ANOVA on the static condition results showed that there was a simple main effect of age on second-order (F[1,15] = 61.689, P < 0.0001) but not on first-order gratings (P > 0.1). Results for moving stimuli showed that contrast thresholds for first-order stimuli decrease with increasing drift speed until 4 Hz where they plateau, whereas those for second-order stimuli continuously increase with drift speed. A three

Table 1

Mean contrast thresholds expressed in modulation depth ( $\pm$ S.D.) for each age group and condition and mean difference between groups (older-younger) is shown for each test condition

Stimulus type	Drift speed (Hz)	Younger	Older	Mean difference <sup>a</sup>
Results for the orientation task (a)				
First-order	Static	$0.0302 (\pm 0.0055)$	$0.0391 (\pm 0.0074)$	0.0095
	2	$0.0074 \ (\pm 0.0018)$	0.0108 (±0.0046)	0.0044*
	4	$0.0046~(\pm 0.0006)$	0.0075 (±0.0036)	0.0036*
	8	$0.0044 \ (\pm 0.0003)$	0.0074 (±0.0052)	0.0040*
Second-order	Static	$0.0640 \ (\pm 0.0156)$	0.1130 (±0.0406)	0.0575*
	2	0.0725 (±0.0176)	0.1334 (±0.0409)	0.0745***
	4	0.0953 (±0.0184)	0.2332 (±0.0804)	0.1494***
	8	$0.1494~(\pm 0.0544)$	$0.3581 (\pm 0.0712)$	0.2151***
Temporally segmented second-order	2	0.1259 (±0.0233)	$0.2930~(\pm 0.0795)$	0.1777***
Results for the direction discrimination ta	sk (b)			
First-order	2	$0.0057 (\pm 0.0012)$	0.0097 (±0.0026)	0.0045*
	4	$0.0049 \ (\pm 0.0003)$	0.0058 (±0.0025)	0.0017
	8	$0.0045~(\pm 0.0004)$	$0.0068 \ (\pm 0.0051)$	0.0034*
Second-order	2	$0.0997 (\pm 0.0230)$	0.1988 (±0.0919)	0.1133**
	4	$0.1196 \ (\pm 0.0401)$	0.2134 (±0.0945)	0.1099*
	8	0.1637 (±0.0813)	0.3847 (±0.1219)	0.2385***
Temporally segmented second-order	2	0.1946 (±0.0412)	$0.4007(\pm 0.0839)$	0.2145***

<sup>a</sup> Asterisk (\*) indicate significant differences, with \* P < 0.05, \*\* P < 0.005 and \*\*\* P < 0.0005.



Fig. 3. Mean contrast thresholds expressed in modulation depth as a function of drift speed on a logarithmic scale. Results are shown for the decreased retinal illumination simulation (full symbols) and for the original data of four younger observers (empty symbols) for first-order (squares), for second-order (circles) and for the segmented second-order motion (triangles) stimuli. (A) Thresholds for the orientation task with the static condition are on the left-hand side of the figure, and those for the three drift speeds (2, 4 and 8 Hz) on the right-hand side of the figure. (B) Thresholds for the direction of motion discrimination task at the three drift speeds. The bars represent the standard error of the mean and are smaller than the symbols where they are not visible.

way ANOVA (age × stimulus type × drift speed) revealed that there was a significant three way interaction (F[2,30] = 13.203, P = 0.0001). As can be seen in the graph (Fig. 1), the three-way interaction is driven by the larger effect of drift speed on second-order stimuli with age. This is not surprising given the assumption that the second-order motion pathway is tuned to lower frequencies than the first-order pathway. A series of analyses were conducted to tease apart the three-way interaction. There was a significant effect of age for first-order motion at all drift speeds (at 2 Hz: F[1,25] = 6.790, P < 0.05, at 4 Hz: F[1,25] = 4.777, P < 0.05, at 8 Hz: F[1,25] = 6.171, P < 0.05). This was also true for second-order motion at all drift speeds (at 2 Hz: F[1,33] = 6.067, P = 0.018, at 4 Hz: F[1,33] = 35.860, P < 0.0001, and at 8 Hz: F[1,33] = 61.550, P < 0.0001). The effect size of age on the first and second-order conditions, as given by  $\omega^2$ was of 0.37 and of 0.42, respectively. The older group's thresholds were significantly higher than those of the younger group (F[1,15] = 36.021, P < 0.0001)for the perception of temporally segmented second-order motion. The difference between older and vounger observers' thresholds is similar for this condition and for the second-order motion stimuli.

#### 2.2.2. Direction of motion task

Results (Fig. 2B; Table 1b) show similar patterns of

threshold change with drift speed for this task as for the orientation task. The older group's thresholds are higher than the younger group's by a factor of approximately 1.5 for the perception of first-order drifting stimuli, and by a factor of approximately 2 for second-order stimuli. A three way ANOVA (age  $\times$ stimulus type  $\times$  drift speed) demonstrated a significant three way interaction (F[2,30] = 9.074, P < 0.001). Separate analyses showed that there was a significant effect of age for first-order motion perception at drift speeds of 2 and 8 Hz (F[1,39] = 12.597, P = 0.001 and F[1,39] = 7.842, P < 0.01, respectively), but not at 4 Hz (P > 0.1). There was a significant effect of age for the perception of second-order motion stimuli at all drift speeds (at 2 Hz: F[1,16] = 12.432, P < 0.005, at 4 Hz: F[1,16] = 9.2980, P = 0.008, and at 8 Hz: F[1,16] = 26.208, P < 0.0001). The effect size of age on the first and second-order conditions, as given by  $\omega^2$ was of 0.29 and of 0.42, respectively. For the temporally segmented second-order motion task, the older group's thresholds were significantly higher than those of the younger group (F[1,15] = 47.710, P < 0.0001). Once more, the difference between older and younger observers' thresholds is similar for this condition and for the second-order motion stimuli.

#### 3. Retinal illumination control condition

Decreased retinal illumination in the elderly arises as a consequence of smaller pupil sizes in older observers when compared to younger observers. Decreased retinal illumination in the elderly may have lead to the difference between older and younger observers' thresholds. The difference in pupil sizes reported here is equivalent to a 0.3 log unit decrease in retinal illumination and is consistent with previous findings (Weale, 1963). In order to simulate this difference, younger observers were tested with neutral density filters.

# 3.1. Method

Four younger observers (mean age  $22.75 \pm 2.06$  years, range 21-25) were re-tested on all conditions with neutral density filters of 0.3 log units. The stimuli and procedure were the same as described in the original experiment.

# 3.2. Results

Thresholds for the four observers tested with the neutral density filters were similar to their thresholds in the original experiment for both the orientation (Fig. 3A) and direction (Fig. 3B) discrimination tasks.

## 4. Noise detection control condition

The noise is an intrinsic part of the second-order but not of the first-order stimulus. As previously stated, the second-order stimuli were modulated between zero and a maximum value so that the overall noise contrast was decreased at lower modulation depths in the second-order but not in the first-order stimulus. Decreased noise detection in the elderly may have lead to the threshold elevation for the perception of the second-order stimulus. In order to ascertain that this was not the case, contrast thresholds were measured for a second-order stimulus in which the noise was maintained at high contrast and were repeated for the original second-order stimulus.

# 4.1. Method

Older (n = 4), mean age  $70.75 \pm 6.02$  years, range 65-79) and younger (n = 4), mean age  $22.75 \pm 2.06$  years, range 21-25) individuals were tested with the original and with the control contrast-defined gratings. The control stimulus consisted of a second-order stimulus as previously defined, but in which the noise was maintained at 45% contrast. The appearance of this second-order stimulus and the original one is the same at maximum modulation depth but differs at lower ones. High contrast (45%) was maintained between adjacent noise elements where the sinusoidal envelope



Fig. 4. Mean contrast thresholds expressed in modulation depth, on a logarithmic scale for four older (full symbols) and four younger observers (empty symbols) for the original second-order stimulus re-tested with the methods of constant stimuli (uniform symbols) and for the control second-order stimulus (hatched symbols). Testing was carried out for three conditions: the static condition, a drifting (4 Hz) orientation condition and a drifting direction (4 Hz) discrimination condition. The standard error of the mean is shown.

peaked, and lower contrasts ( < 45%) resulted between adjacent noise elements where the envelope was at a minimum.

The same tasks as previously described were carriedout and contrast thresholds, expressed in modulation depth (as in the original experiment) were measured for the static condition and at a drift speed of 4 Hz. The method of constant stimuli was used for both stimuli (original and control).

# 4.2. Results

The four observers in each group had the same threshold for the static and drifting (4 Hz) control stimuli as they did for the original second-order stimuli (Fig. 4) with both types of tasks.

#### 5. Discussion and conclusion

Advanced age results in a larger threshold elevation for the perception of second-order stimuli than for the perception of first-order stimuli. The control conditions show that these findings are not a result of senile meiosis or of decreased noise detection.

The present data on static first-order stimuli is in accordance with previous studies which found no effect of age on the perception of a 1 cpd static grating (Lundh et al. 1983; Owsley et al. 1983; Kline, 1987; Tulunay-Keesey et al. 1988; Elliott et al. 1990). The results for drifting first-order gratings are consistent with the studies that showed an effect of age on low spatial and low to medium temporal frequencies (Owsley et al. 1983; Kline, 1987).

Thresholds for second-order stimuli across drift speed in the younger group are consistent with those previously reported by Smith and Ledgeway (1997) for both the orientation and direction discrimination tasks. Thresholds for the perception of second-order stimuli (including that of the temporally-segmented motion stimulus) approximately doubled between younger and older groups. This difference is similar to that reported by Trick and Silverman (1991) who found a doubling of percent coherence thresholds for the perception of global motion between the ages of 20 and 80. The perception of global motion requires pooling of local motion vectors over space and time, and thus a relatively high level of cortical integration (Williams, Phillips & Sekuler, 1986; Williams & Phillips, 1987; Watamaniuk, Sekuler & Williams, 1988). As previously stated, the perception of second-order stimuli would also require relatively more complex cortical analysis, and the perception of both types of stimuli may thus be affected in similar ways by aging.

The larger effect of age (threshold elevation) on the sensitivity to second-order than to first-order stimuli

suggests a dissociation between their respective underlying mechanisms and may be explained by the physiological changes mentioned in the introduction. Any functional decreases would be expected to accumulate throughout a particular cortical process, and to become more influential in more elaborate processes (more areas and connections). As a result, simpler mechanisms (involving fewer steps and interactions) may be less affected by advanced age, and decreases in sensitivity become apparent in more complex mechanisms such as those underlying the perception of second-order and global motion stimuli. Though a larger threshold elevation was expected for temporally-segmented second-order motion stimuli than for contrast-defined second-order motion stimuli, the magnitude of the sensitivity decrease was similar for both conditions. The perception of global motion stimuli is assumed to require a relatively larger network than that of second-order stimuli yet decreases in sensitivity with age are similar for the perception of both types of motion. It may simply be that aging does not have a differential effect on the perception of these various stimuli because the extent of cortical processing required is not sufficiently disparate from one another.

In conclusion, we propose that the decrease in sensitivity for second-order stimuli in the elderly may result from the more numerous processing steps required for the analysis of second-order and other complex stimuli. In terms of daily activities, the findings suggest that age-related declines in sensitivity would be more evident in complex environments. For example, when at home, surroundings are familiar and little integration is required for performing daily tasks. When in a public place however, numerous unfamiliar objects and crowds of people moving about in different directions and at different speeds complicate the visual scene. Simply finding a direction of flow to walk with, within the randomly-moving crowd requires a certain level of integration. This may be one of the possible explanations for the reluctance of many older individuals to leave their homes.

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