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Aging and Visual Masking: Sensory and Attentional Factors

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Visual tasks can yield quantitatively similar patterns of performance that reflect different underlying mechanisms in younger and older observers. In 3 experiments, we used the visual masking task of J. T. Enns and V. Di Lollo (1997) to examine 2 of these mechanisms: stimulus contrast and attention. Performance appeared to be equivalent for younger and older observers in some circumstances, although manipulation of contrast and attention suggested that older observers may use focal attention to enhance the perceptual clarity of the target. For older observers, impoverished visual representations may more readily be eliminated by manipulation of attention or by the presence of a mask, indicating that both attention and stimulus quality are important influences on performance.

When older experimental participants in a study are asked to consider differences in the performance of younger and older adults on visual tasks, they are most likely to mention age-related changes in peripheral factors. These include changes to the lens that influence visual clarity or the ability to focus on near objects, such as a book, and eye diseases, such as glaucoma, cataracts, or macular degeneration, both of which become more common with advancing age (see Michaels, 1993, for a review). Typically not considered are the contribution of central or postretinal processes to visual processing and the possibility that age-related changes to these central processes may also play an important role in age-related changes in vision.

In this article, we examine the phenomenon of visual masking in older adults. Visual masking is frequently described as resulting from peripheral effects, but there is evidence of a strong central component to this phenomenon. As such, masking represents an excellent candidate for examining the interaction between peripheral and central factors in older adult vision. Understanding the nature of this interaction is critical for developing age-related models of human cognition (Schneider & Pichora-Fuller, 2001). In the following paragraphs, we briefly describe visual masking and refer to the literature on peripheral models of visual masking. Our primary consideration, however, will be to explain how data from younger adults suggest an important role for a central process in masking, namely attention, and to show how these data may explain the strong role for central processes in masking for older adults that has been found in previous research. We conclude with a discussion of how these effects may interact with peripheral changes in older adult vision and briefly describe the three experiments we conducted to investigate these effects.

Visual Masking

Visual masking is the reduction in visibility of one stimulus by the presentation of another stimulus in near or concurrent spatial and temporal proximity. There are various forms of visual masking, each defined by the temporal position of the masking stimulus relative to the target. For example, in paracontrast masking, the mask occurs before the target, whereas in metacontrast masking, the mask occurs after the target. In this article, we refer more generally to a *contour mask* as a masking stimulus that appears before or after the target and that forms a contour around the target but does not occupy the same spatial position. Theories of contour masking generally assume that the mechanisms underlying masking are peripheral (Breitmeyer, 1984; Breitmeyer & Ganz, 1976; Breitmeyer & Williams, 1990; Burr, 1984; Weisstein, Ozog, & Szoc, 1975). The Breitmeyer model, for example, focuses on the inhibitory connections between parvocellular and magnocellular retinal ganglion cells and clearly places the source of masking in the periphery of the visual system.

However, work by Enns and Di Lollo (1997) showed that central processes also have an important role in masking. Because it is known that visual attention can enhance or decrease the processing of visual information in the visual cortex (e.g., Treue & Maunsell, 1996; see Luck & Hillyard, 2000, for a recent review), Enns and Di Lollo examined attention as a candidate central process. In their experiments, they demonstrated that objects that normally would not serve as a mask may do so when visual attention is spread across a large spatial region. Enns and Di Lollo called this form of masking *attentional masking by object substitution.*

To understand the difference between this and contour masking, consider the two types of masks depicted in Figure 1. The mask on the left is a typical contour mask. The surrounding frame crowds the target diamond but does not overlap with it. In comparison, the properties of the four-square mask (or *object mask*) on the right make it too weak to serve as a mask under typical viewing conditions. In the experiments of Enns and Di Lollo (1997), for example, the object mask did not significantly reduce observer accuracy for detecting the target when the mask and target were presented at a location near fixation and viewed with focal attention. However, when the target was presented with spatial uncertainty (i.e., in one of three possible locations) so that attention was spread across a larger spatial extent, the four-square mask produced masking, or a reduction in the ability to accurately identify the target. Because this occurred only under conditions in which

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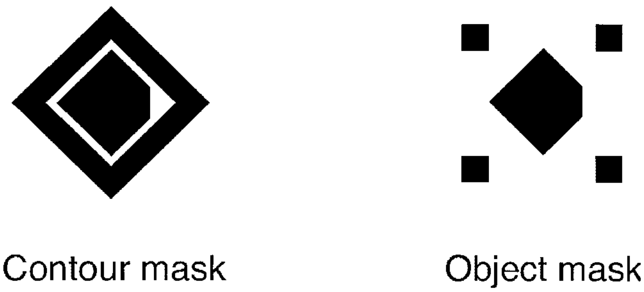

Figure 1. Diagram of the two types of masks. The target is the center diamond. The contour mask on the left produces masking through metacontrast. The four-dot or object mask on the right produces masking through object-substitution.

the attentional gradient was spread across a large spatial extent and was strongest at locations where the gradient of spatial attention was weakest (e.g., parafoveal locations), Enns and Di Lollo suggested that it was a form of attentional masking. They suggested that the representation of the four dots eliminated the representation of the target (see also Brehaut, Enns, & Di Lollo, 1999; Giesbrecht & Di Lollo, 1998). In other words, at locations where the attentional gradient is relatively weak and information is coded with a low spatiotemporal resolution, object representations are vulnerable to substitution by other competing and spatiotemporally contiguous representations. Thus, though contour masking occurs primarily because of peripheral effects, object substitution is primarily a central or postretinal effect.

Masking and Aging

The data of Enns and Di Lollo (1997) are interesting for understanding the aging visual system because the limited number of studies on aging and masking have proposed that central or postretinal changes with age play an important role in masking in older adults. For example, experiments using dichoptically presented masks and targets on older adults to eliminate retinal effects (Hertzog, Williams, & Walsh, 1976; Kline & Birren, 1975; Walsh, 1976) have shown that older adults experience robust masking effects even when the mask and target are shown to different eyes, indicating that the locus of masking effects must be postretinal in nature (Turvey, 1973). Although these studies have confirmed a role for central processes in masking with older adults, it is unclear what central process is affected. Di Lollo, Arnett, and Kruk (1982) suggested that backward masking in older adults may be due to "interference with processes of classification and categorization at later processing stages" (p. 236). This is presumably due to a reduction in perceptual processing speed with age, such that the increased time to identify the target results in greater interference by the trailing mask. Given the more recent results of Enns and Di Lollo, attention seems to be a more likely candidate for the central process proposed to account for age-related effects in visual masking. What makes the attentional account particularly interesting for understanding aging and vision is Enns and Di Lollo's suggestion that attentional masking or object substitution interacts with the quality of visual information. Weak spatiotemporal representations are more easily eliminated by weak masking stimuli. In the aging visual system, changes in peripheral and central processes underlying functions such as contrast and acuity reduce the spatiotemporal resolution of visual information. Thus, older adults may be more vulnerable to the object substitution effect indicating that masking in older adults is actually due to an interaction of sensory and attentional effects.

Present Experiments

In the present experiments, we examined the attentional and sensory factors contributing to visual masking in older and younger adults. Building on the proposal that central mechanisms account for masking for older adults and on the data of Enns and Di Lollo (1997), who indicated that attention plays a role in masking when the spatiotemporal resolution of a stimulus is weak, we hypothesized that the reduction in visual clarity accompanying aging creates a state of low spatiotemporal resolution, which would promote attentional masking in older adults. Thus, in older adults, masking via object substitution can occur even under conditions of focused attention because reduced stimulus clarity as provided by the aging eye leaves target information vulnerable to elimination via object substitution. Three experiments were conducted to examine this hypothesis. In the first experiment, we compared younger and older adults, using both contour and object masks under conditions of focused attention and attention spread over a larger spatial region. We wanted to confirm the results of Enns and Di Lollo and to determine whether older adults would show attentional masking under conditions of focal attention as predicted. In a second experiment, we used dichoptic presentation to confirm that observed effects with the object mask were due to a central, and not a peripheral, process. Finally, in a third experiment, we sought to support the hypothesis that object substitution effects in older adults were the result of weakened spatiotemporal resolution by manipulating the spatiotemporal resolution of stimuli presented to a group of younger observers. If the younger observers' pattern of data with the object mask under conditions of focal attention and low target spatiotemporal resolution became qualitatively similar to the pattern of older adults, then we could conclude that the effects in older adults were consistent with the hypothesis that a similarly impoverished representation was eliminated through the process of object substitution.

Experiment 1

In the first experiment, we replicated the experiments of Enns and Di Lollo (1997) and added a sample of older observers. The design contained two types of masks, contour and object. Although the contour mask produces masking in younger adults even when attention is focused at a single location, the object mask does not. When attention is spread across a larger spatial extent than the focused attention condition, however, the object mask does serve as a backward mask, with the largest masking effect typically when the object mask appears 50 ms after the presentation of the target. Enns and Di Lollo suggested that this represents a process of object substitution, in which the representation of the mask replaces the representation of the target (see also Brehaut, Enns, & Di Lollo, 1999; Giesbrecht & Di Lollo, 1998).

We predicted, on the basis of previous research (Hertzog, Williams, & Walsh, 1976; Kline & Birren, 1975; Walsh, 1976) and on the presence of declines in low-level sensory abilities such as acuity and contrast sensitivity, which would influence target clarity (see Spear, 1993, for an excellent overview of age-related changes to these and other visual functions and Schneider & Pichora-Fuller, 2001, for a review of perceptual and cognitive interactions), that the older observers would show larger contour masking. Also, in the older adults, the object mask should produce masking in the presence of focused attention (i.e., when only one mask–target location was used), because the weakened spatiotemporal characteristics of the target leave it susceptible to elimination via object substitution.

Method

Participants

Twenty community-dwelling older adults (12 women and 8 men; mean age = 75.9 years; range = 68–89 years) participated in exchange for monetary compensation. All older adult participants reported normal visual function and an absence of eye disease. Participants completed a number of visual screening measures as detailed below. Data were also collected from 19 younger adults who participated in exchange for class credit (7 men and 12 women; mean age = 21.2 years; range = 18–25 years).

Materials

We measured far visual acuity with the Graham Field Far Eye Chart (at 10 ft [3.05 m]); contrast sensitivity with the VisTech Consultants Contrast Sensitivity Chart (Model 6500-configuration C; at 10 ft [3.05 m]), and near visual acuity with the Precision Vision Logarithmic Near Visual Acuity Chart (at 16 in. [40.6 cm]; all eye charts listed, Vistech Consultants, Dayton, OH).

There were three types of stimuli in the masking task. The stimuli were derived from the study by Enns and Di Lollo (1997). All stimuli were black (0.01 cd/m^2) on a white background (82.5 cd/m^2) and were presented in a darkened room using a personal computer with a 45-cm monitor set at a distance of 60 cm. The target consisted of a diamond (0.62° in vertical extent) with a missing point (0.17°) on either the left or right side. The contour mask consisted of a diamond-shaped frame that fit around the target (0.20° in width and one pixel from the target). The object mask consisted of four small squares (0.20°) that were placed on a notional square (1.0° on each side). The squares had a minimum separation from the target of 0.35°. Enns and Di Lollo found that these squares did not serve as a mask for younger observers when viewed centrally with focused attention (see also Breitmeyer, 1984; Growney, Weisstein, & Cox, 1977). In addition to the primary stimuli, a fixation point was used consisting of two short vertical lines (2.0° above and below the location of the central stimulus).

There were three main conditions in the experiment. The first condition, in which the target appeared alone in the central location, served as practice. The second condition, in which the target and mask were presented in the central location only, assessed the effect of the masks under conditions of full attention. Contour and object masks appeared equally often and were randomly assigned from trial to trial. In the third condition, the target and mask were randomly assigned one of three locations, one central and two parafoveal (3.0° left and right of center). Thus, the target and the mask appeared in the same location on only one third of the trials. Comparison of the third divided-attention condition (in which observers were required to spread their attention across a large spatial region in order to detect the target) with the second full-attention condition (a single location baseline) provided a measure of the influence of attention on masking.

Across all trials, the durations of the target and mask were 32 ms. The mask, when present, was presented at 1 of 8 stimulus onset asynchronies (SOAs; −150, −100, −50, 0, 50, 100, 150, or 300 ms relative to target). In the first condition, for each observer, there were 72 trials for the no-mask condition. In the second condition, there were 20 trials per combination of mask type and SOA (320 trials). In the third condition (three possible locations), for the same-location condition, there were 8 and 16 trials for the central and peripheral conditions for each SOA, respectively. For the different-location condition, there were 16 and 32 trials in the central and peripheral conditions for each SOA, respectively. The three-location condition had two blocks with 288 trials in each block.

Procedure

On arrival at the laboratory, the participants were asked to perform a series of static visual abilities tasks (measures of contrast sensitivity and near and far visual acuity). The participants then performed the attentional masking task. Participants were instructed that they would be performing a target identification task. Their task would be to determine whether a briefly presented diamond shape was missing its left or right corner and to respond by pressing the mouse button corresponding to the missing corner (left or right). They were also informed that the display would be very brief and occasionally made more difficult by the presence of competing visual information. Participants were asked to respond as accurately as possible, to not worry about response speed, and to make their best guess when unsure of the correct answer. Participants were further instructed to fixate between the vertical lines that appeared at the beginning of the trial.

After these initial instructions, the participants completed the target-only displays. After completing these displays, participants were informed that on subsequent trials, displays would contain a mask that might occur before or after the target and that this mask might make the target difficult to detect. Participants were informed that in the second set of displays, the mask and target would appear at the fixation location, but in the final two sets of displays, the mask and target might appear centrally or in peripheral visual locations and that the mask and target might not appear in the same location. Participants were informed to maintain fixation centrally and to not shift gaze to the mask location, as it would not predict the location of the target with more than chance accuracy (see Atchley, Kramer, & Hillstrom, 2000; Folk, Remington, & Johnston, 1992). After these instructions, participants completed the remaining conditions. This session took approximately 70–90 min to complete.

Results

General Analytic Strategy

The results of Enns and Di Lollo (1997) were used to guide our data analysis. First, neither the contour mask nor the object mask should serve as a forward mask at the longest mask-to-target SOAs (−150 and −100 ms). Therefore, these two conditions were used to establish a baseline of performance for each group against which masking can be assessed at critical SOAs. Each mask type served as its own baseline, and in the three-location case, only trials in which the target and the mask occurred at the same location were used for calculation of the baseline. The advantage of this approach was most obvious in the three-location condition, in which the conditions could be used as a baseline where the mask and target appeared at different target locations (e.g., comparing target left/mask left to target left/mask right). When the mask appeared at a location other than the target (e.g., when the target was at the far left and the mask was at the far right location), however, observer attention might be at the mask location and not the target location. Ideally, we wanted to assess the effect of the mask when attention was at the target location and not shifted to a different location, even when attention was spread across a large spatial region (as in the three-location condition).

A second component of the analysis concerned the critical SOA to be examined. The work of Enns and Di Lollo (1997) suggested that masking should be strongest in the 50-ms SOA case across all conditions. Therefore, in all experiments, we performed planned comparisons of this condition to the baseline in all conditions. Post hoc tests of other SOAs were included where appropriate. Third, although omnibus tests that include age as a variable were included in the general analysis, we used estimates of effect size for each group (Cohen's *d;* Cohen, 1988) to provide an assessment of the relative effect of the masks across the different age groups. As with other analyses, effect sizes were comparisons of conditions of interest (generally the 50-ms case) to the baseline condition, unless otherwise specified. Effect sizes of around 0.2 were considered small, 0.5 were medium, and 0.8 were large. Of critical interest was not simply whether sensory and attentional masking occurs with age but whether the magnitude of masking was exacerbated by age.

Data Screening

On the basis of previous research, it was clear that older observers would have difficulty with the masking task and that the addition of an attention manipulation would further compound this difficulty, potentially yielding a number of participants for whom performance would be at or near chance. We chose a sample size of older observers that was about twice as large as typically found in research of this type (e.g., Hertzog, Williams, & Walsh, 1976; Kline & Birren, 1975; Walsh, 1976), anticipating the loss of participants with highly inaccurate data. In Experiment 1, data from 1 older observer were excluded because he declined to complete the task. Additionally, a cutoff of 70% average accuracy across all SOAs and mask types in the central-only condition was established, resulting in the loss of an additional 9 older participants. This value was chosen because it was close to a typical threshold value for psychophysical research in two-alternative or two-interval forced-choice paradigms, and it preserved the largest number of participants from the initial group. The remaining sample size ($n = 10$) was typical for studies of this type. An analysis of the characteristics of the sample is presented in Table 1.

Table 1
Visual Acuity, Contrast Sensitivity at Various Spatial Frequencies, Chronological Age, and Gender Ratios for the Observers in Experiment 1

	Observer	
Measure	Older	Younger
Gender ratio (women:men)	7:3	12:7
Age (years)	73.8	21.2
Near visual acuity	20/35.8	20/26.9
Far visual acuity	20/27.8	20/19.7
Contrast sensitivity		
Spatial frequency (cycles/deg.)		
1.5	30.5	40.6
3	72.7	84.0
6	57.5	75.0
12	20.1	33.2
18	6.4	14.4

Note. deg. = degree

Central Condition Only

Data for this condition are presented in Figure 2. The data were analyzed using a three-way analysis of variance (ANOVA). The effect of age was significant, $F(1, 27) = 60.45$, $MSE = 182.9$, $p < .01$, such that older observers performed less accurately overall (mean accuracy = 86.9%) than younger observers (mean accuracy = 97.1%). The effects of mask type, $F(1, 27) = 43.46$, $MSE = 42.1$, $p < .01$, and SOA, $F(7, 189) = 20.7$, $MSE = 76.9$, $p < .01$, were also significant. The interaction of age and mask type, $F(1, 27) = 23.31$, $MSE = 42.1$, $p < .01$, age and SOA, $F(7, 189) = 8.40$, $MSE = 53.8$, $p < .01$, and mask type and SOA, $F(7, 189) = 2.38$, $MSE = 53.8$, $p < .05$, were also significant.

Younger adults. The baseline performances for the contour mask (98.2% correct) and object mask (97.1% correct) were not reliably different ($F < 1.0$). Planned comparisons at 50 ms SOA for the contour and object masks showed contour masking (87.4% correct), $F(1, 27) = 10.43$, $MSE = 141.4$, $p < .01$, but no object masking (96.8% correct; $F < 1$; $d < 0.1$). The contour mask produced a moderate to large effect ($d = 0.69$), whereas the effect size for the central mask was .23.

Older adults. The baseline performance (89.5% correct) for the contour mask was significantly lower than that of the object mask (96.0% correct), $F(1, 27) = 10.55$, $MSE = 40.1$, $p < .01$. The effect size estimates for masking effects as described below are presented in Table 2. Planned comparisons at the 50-ms SOA for the contour and object masks showed a large effect for the contour mask (62.0% correct; $d = 0.94$), $F(1, 27) = 35.66$, $MSE = 141.4$, $p < .01$, and the object mask (72.0% correct; $d = 0.89$), $F(1, 27) = 31.02$, $MSE = 123.8$, $p < .01$. Performance was significantly worse in the contour mask condition, $F(1, 27) = 10.02$, $MSE = 49.9$, $p < .01$. The data in Figure 2 suggest masking at SOAs other than 50 ms for the older adults. To determine whether this was the case, we performed post hoc analyses at the 0-ms and 100-ms SOA conditions for both mask types for the older adults. At the 0-ms SOA, there was moderate contour masking, $F(1, 27) = 7.53$, $MSE = 138.4$, $p < .05$; 77.2% correct; $d = 0.57$, and small object masking, $F(1, 27) = 4.73$, $MSE = 22.6$, $p < .05$; 91.7% correct; $d = 0.36$. At the 100-ms SOA there was moderate contour masking, $F(1, 27) = 6.55$, $MSE = 73.5$, $p < .05$; 81.3% correct; $d = 0.56$, and a large effect for the object mask, $F(1, 27) = 13.34$, $MSE = 51.0$, $p < .01$; 85.9% correct; $d = 0.86$. Finally, a comparison of the performance of younger and older observers at 50-ms SOA showed that older adults performed significantly worse with both the contour mask, $F(1, 27) = 26.30$, $MSE = 160.3$, $p < .01$ (older adult mean = 62.0%, younger adult mean = 87.4%) and object mask, $F(1, 27) = 30.57$, $MSE = 132.2$, $p < .01$ (older adult mean = 72.0%, younger adult mean = 96.8%).

Three-Location Condition

Data for this condition are presented in Figure 3. The effect of age was significant, $F(1, 27) = 24.54$, $MSE = 1{,}938.3$, $p < .01$, such that older observers performed less accurately overall (mean accuracy = 69.7%) than younger observers (mean accuracy = 84.8%). The effects of mask location, $F(1, 27) = 143.22$, $MSE =$

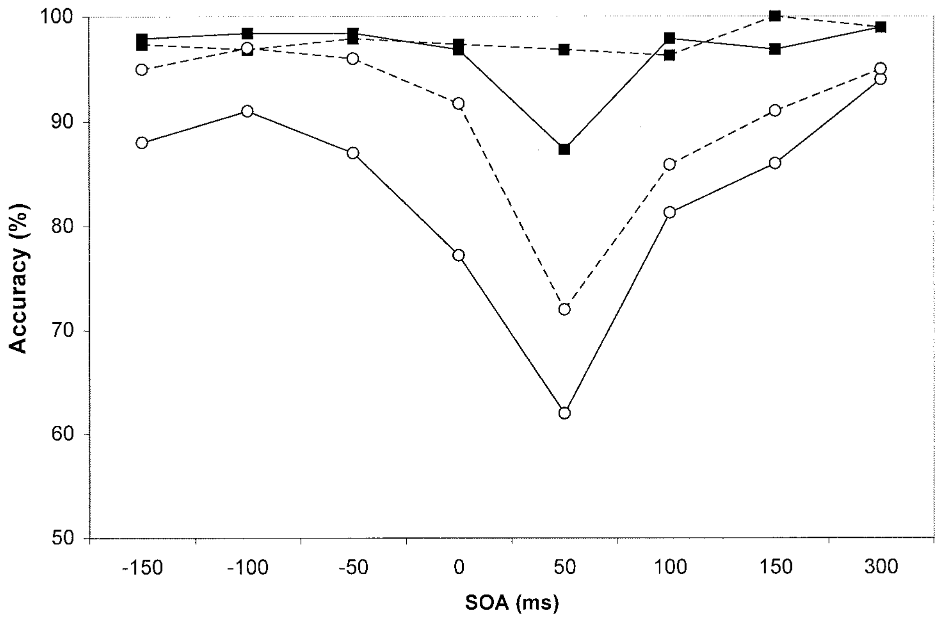

Figure 2. Masking performance in the central-only condition. Data for younger observers are on the top (black squares), and older observers are on the bottom (open circles). Dashed lines denote the object mask presentation, and solid lines denote the contour mask. SOA = stimulus onset asynchrony

485.6, $p < .01$, and SOA, $F(7, 189) = 9.27$, $MSE = 275.0$, $p < .01$, were also significant. No other effects or interactions were significant (Fs < 2.5). However, further planned comparisons based on the a priori motivating questions of interest are reported below.

Younger adults—central location. At the central location, the baseline performances for the contour mask (97.4% correct) and the object mask (96.7% correct) were equivalent ($F < 1.0$). Planned comparisons at 50-ms SOA for the contour and object masks showed contour masking (84.2% correct), $F(1, 27) = 7.15$, $MSE = 306.5$, $p < .05$, and object masking (86.8% correct), $F(1, 27) = 4.62$, $MSE = 266.8$, $p < .05$. The contour mask and object mask produced moderate effects (ds = 0.59 and 0.51, respectively).

Younger adults—parafoveal location. The baseline performances for the contour mask (78.2% correct) and the object mask (81.3% correct) at parafoveal locations were equivalent ($F < 1.0$). Planned comparisons at 50-ms SOA for the contour and object masks showed contour masking (56.6% correct), $F(1, 27) = 15.36$, $MSE = 388.6$, $p < .01$, and object masking (63.8% correct), $F(1, 27) = 8.73$, $MSE = 441.0$, $p < .01$. The contour mask and object mask produced moderate to large effects (ds = 0.72 and 0.54, respectively).

Older adults—central location. Baseline performance rates with the contour mask (86.3% correct) and the object mask (80.0% correct) were significantly different, $F(1, 27) = 5.02$, $MSE = 77.8$, $p < .05$. Planned comparisons at 50-ms SOA for the contour and object masks showed contour masking (67.5% correct), $F(1, 27) = 7.64$, $MSE = 306.5$, $p < .05$. Object masking (67.5% correct) was marginally significant, $F(1, 27) = 3.90$, $MSE = 266.8$, $p < .06$, due to high variability of the baseline. The contour mask and object mask produced moderate effects (ds = 0.66 and 0.54, respectively). Additional post hoc analyses revealed that the contour mask produced a significant masking effect at both 100-ms SOA (65.0% correct), $F(1, 27) = 20.59$, $MSE = 146.2$, $p < .01$, and the 150-ms SOA (65.0% correct), $F(1, 27) = 18.53$, $MSE = 162.4$, $p < .01$. The contour mask produced moderate effects in the 100- and 150-ms SOA conditions (ds = 0.70 and 0.70, respectively).

Table 2
Effect Size (Cohen's d) of Masking at the 50-millisecond SOA in Experiment 1 for the Conditions, Mask Types, and Target Locations in Each of the Age Groups

Mask type and location	Condition: Central	Condition: Three location
Younger observer		
Contour		
Central	.69	.59
Parafoveal		.72
Object		
Central	.23	.51
Parafoveal		.54
Older observer		
Contour		
Central	.94	.66
Parafoveal		.16
Object		
Central	.89	.54
Parafoveal		.40

Note. Small effects = 0.20; medium effects = 0.50; large effects = 0.80 (Cohen, 1988).

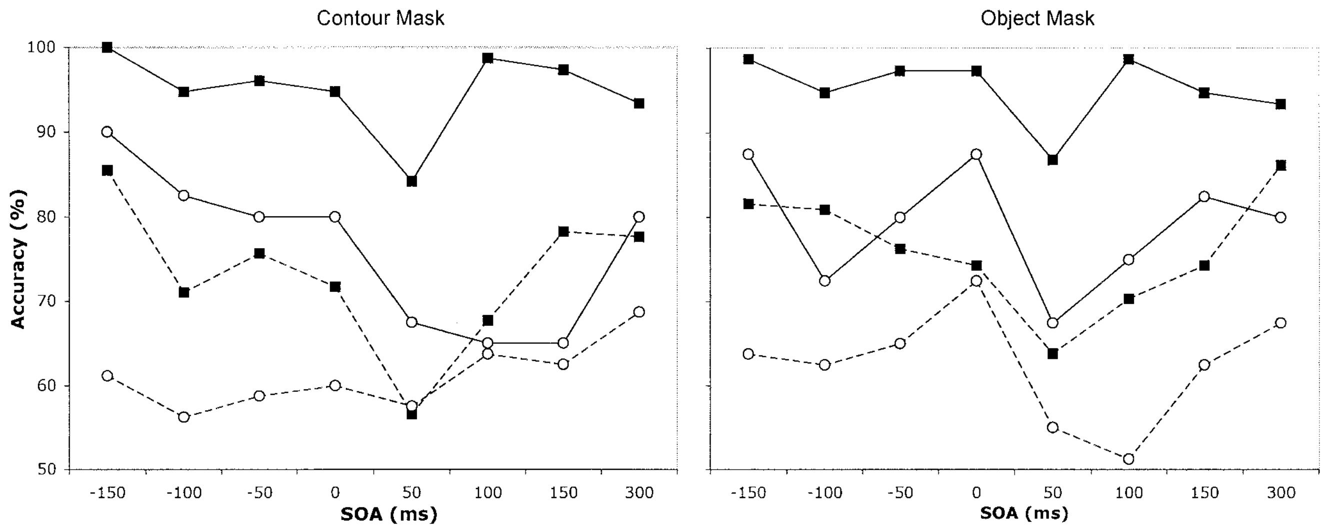

Figure 3. Masking performance in the three-location condition. Contour mask data are on the left, and object mask data are on the right. Data for younger observers are presented with black squares, and older observers are presented with open circles. Solid lines denote the central location presentation, and dashed lines denote the parafoveal location. SOA = stimulus onset asynchrony

Older adults—parafoveal location. The baseline performances for the contour mask (58.7% correct) and the object mask (63.2% correct) did not differ significantly ($F < 1.0$). Planned comparisons at 50-ms SOA for the contour and object masks failed to show contour masking (57.5% correct; $F < 1.0$), and showed marginal object masking (55.0% correct), $F(1, 27) = 3.54$, $MSE = 265.3$, $p < .08$. The contour mask effect size was small ($d = .16$), and the object mask effect was small ($d = 0.40$).

Effect of Attention

An additional set of post hoc analyses were performed to assess the effect of requiring observers to spread attention in the three-location condition with the object mask. One question was whether the requirement to spread attention decreased performance for the younger observers even without the presence of a mask. Of further interest was any evidence that the requirement to spread attention significantly decreased baseline performance of the older observers in the three-location condition, in particular because the performance of these observers suffered from floor effects.

We compared performance for the younger and older observers with the object mask in two conditions. First, we compared baseline performance (in which the mask appeared but was too temporally distant to have an effect on the target) in the central-only (focused attention) condition with the central location in the three-location (spread attention) condition. For the younger observers, baseline performance was equivalent ($F < 1.0$) between the central-only and central location in the three-location condition (mean accuracy = 97.1% and 96.7%, respectively). For the older observers, however, spreading attention was related to a reduction in baseline accuracy between the central-only and central location in the three-location conditions (mean accuracy = 96.0% and 79.9%, respectively), $F(1, 27) = 28.94$, $MSE = 90.0$, $p < .01$. There were no differences between the younger and older observer central-only baselines, but the baseline of the older observers in the central location in the three-location condition was significantly lower than the baseline of the younger observers, $F(1, 27) = 13.91$, $MSE = 116.4$, $p < .01$.

A second set of analyses revealed the floor effects in the older adult data. For the younger adults, performance at the critical 50-ms SOA decreased from 96.8% mean accuracy to 86.8% mean accuracy when attention was spread across the display in the three-location condition, $F(1, 27) = 4.83$, $MSE = 196.7$, $p < .05$, demonstrating the object substitution effect. However, the older adults did not show the object substitution effect (central-only location mean accuracy = 72.0%; three-location mean accuracy = 67.5%; $F < 1.0$).

Discussion

The purpose of Experiment 1 was to investigate the contribution of attention to visual masking effects in younger and older adults. When the target mask was presented in the central visual field only (focused attention condition), the younger observers showed a moderate to large effect for the contour mask and no effect for the object mask. The older observers showed large masking effects for both the contour and object masks, consistent with the hypothesis that their representation of the target was spatiotemporally weak and subject to elimination via object substitution. The same effect occurred only for the younger observers when attention was divided across three locations. Although the older observers also demonstrated object masking in the divided attention condition, there was evidence that the influence of the masks had a longer time course. For example, the contour mask produced moderate masking in the younger observers for the central and parafoveal target locations at 50-ms SOA. In the older observers, moderate to strong masking was found from 50-ms to 150-ms SOA. (Floor effects prevented a similar analysis of the parafoveal conditions.)

The data also suggested that the requirement to spread attention had a larger impact on older adult performance. Even though the baseline performance of younger and older adults with the object mask in the central location condition (when attention could be focused at one location) was similar, only older adults experienced a drop in baseline performance when they were required to spread attention across three possible target locations. This pattern of data suggests that older adults were able to use focused attention to increase baseline performance in the central-only condition, but when the size of the attentional gradient was increased, this benefit was lost.

Given these results, what can be concluded with respect to the initial questions? First, although the younger observers showed only contour masking with focal attention (the central-only condition), performance of the older observers was strongly influenced by both the contour and object masks even when attention was focused. Equivalent baseline performance for the older and younger observers under conditions of focused attention indicated older observers were capable of detecting the target accurately, but the reduced baseline performance for older observers when attention was spread reveals that older observers needed attention to accurately detect the target. This suggests the target was spatiotemporally weak for the older observers, as one would expect given normal visual impairments with age. Given the viewing distance, an analysis of the far acuity data would seem to be most appropriate. An analysis of the far acuity data is consistent with differences in spatiotemporal resolution for younger and older observers: Older adult far acuity (20/27.8) was significantly lower than that of younger adults (20/19.7), $t(19) = 3.95$, $p < .05$. These results are consistent with the hypothesis that the increase in masking for the older observers is the result of object substitution operating on targets with reduced spatiotemporal resolution.

In younger adults, the object substitution effect is strongest when attention is spread and at parafoveal locations where the representation is weakest. In older adults, the aging visual system weakens the representation of the target. Attentional capacity seems necessary to enhance the target representation so the observer can perform target discrimination. However, the presence of an object substitution effect in older observers under conditions of focal attention suggests this representation continues to be weak enough for object substitution to take place, because it can be eliminated by the object mask. To confirm this account, we must first demonstrate additional results. First (Experiment 2), we must ensure that the object mask is actually producing its effects via a central mechanism (object substitution). Second (Experiment 3), we must confirm the conclusion that the results from the older observers were due to reduced spatiotemporal target resolution by attempting to "age" a sample of younger observers to obtain a similar pattern of performance.

Experiment 2

The effects of the object mask are presumed to be due to changes in the representation at the location of the target, rather than an effect of the mask at a retinal level. In younger observers, this is shown by a lack of masking with an object mask when attention is focused. In older observers, however, the presence of masking effects in the focused attention condition raises the possibility of masking effects other than via object substitution. To control for this possibility, we employed a dichoptic masking procedure that has previously been used to investigate retinal and postretinal contributions to masking (Kline & Birren, 1975; Walsh, 1976). In this procedure, the mask and target can be presented to individual eyes. Postretinal masking influences, including object substitution, can be assessed by performance on trials in which the target and mask are presented to different eyes. If postretinal effects can account for the masking performance observed in the first experiment for the older observers with the object mask, then the object mask should produce masking even under dichoptic conditions. If the object mask is producing masking in older observers via retinal mechanisms, however, then masking should be greatest when both target and mask appear in the same eye.

Method

The stimuli and procedure in Experiment 2 were similar to those used in Experiment 1, except as noted below.

Participants

Eighteen community-dwelling older adults (11 women and 7 men; mean age = 72.3 years) participated in exchange for monetary compensation. All older adult participants reported normal visual function and an absence of eye disease. Data from 10 younger adults (5 men and 5 women; mean age = 22.3 years) were also collected. All observers had normal or corrected-to-normal far acuity (20/30 or better).

Materials

In this experiment, we used the object mask only, and presented it to the central visual field only. Dichoptic presentation was achieved by using a phase haploscope (Stereographic Corporation, San Rafael, CA). An LCD shutter system was placed in front of the monitor, repolarized at a rate of 120 Hz, and synchronized to the presentation of one of two images (each image was presented at 60 Hz). Observers wore polarized lenses that allowed light from the monitor to enter either eye at a rate of 60 Hz. The lenses were synchronized with the polarization of the LCD shutter. The polarized lenses could be worn comfortably over any eye correction.

Procedure

Three blocks of trials were performed, corresponding to the three conditions in the Experiment 1. The target and mask were always presented centrally. In all blocks, left and right eye presentation of the target and mask were counterbalanced and randomized within the block. Eye was not a factor in the design and data were collapsed across eye presentation in the monoptic condition. All trials were completed while participants wore the polarized lenses. In the first block of 24 trials, observers performed the target discrimination task without the mask. In the second block of 36 trials, observers performed the target discrimination task with the mask at a slower than normal pace. In this block, the target was displayed for 150 ms, the mask was displayed for 150 ms, and the mask–target SOAs of −500, 0, and 500 ms were used. The final block of 144 trials was similar to the central-only condition (block 2) of Experiment 1. In Experiment 2, six SOAs were used: −100, −50, 0, 50, 100, and 150 ms. In addition, on half of the trials, the mask and target were presented to different eyes, whereas on the remaining half of the trials, the mask and target were presented to different eyes. Thus, this experiment included a 2 (age: younger vs. older) × 2 (viewing condition: monoptic vs. dichoptic) × 6 (SOA) design.

Results

To investigate the potential effects of sensory and postretinal masking processes, it was important to collect data from a set of observers whose performance was substantially above baseline. One concern was that the reduction in contrast caused by the polarizing lenses in the haploscope would make the stimuli too difficult for some of the older observers. (The effect of contrast is examined in Experiment 3.) Therefore, we chose a more stringent set of exclusion criteria for observers in Experiment 2. To be included, observers first needed to have target discrimination rates in the first block of greater than 70%. One younger observer (50% target discrimination rate) and 4 older observers (average target discrimination rate of 62.5%) were subsequently excluded. The remaining younger and older observers had average target detection rates of 91.7% and 81.8%, respectively. The second exclusion criterion required that an observer's average baseline data for the third block (the data for the −100- and −50-ms SOA conditions) be at least 70% correct. No younger observers and 4 older observers (average of 54.4%) were excluded with this criterion. The remaining younger and older observers exhibited average baseline performances of 92.3% and 74.2%, respectively.

The data for the remaining 9 younger and 10 older observers were analyzed with a three-way ANOVA and are presented in Figure 4. The effect of age was significant, $F(1, 18) = 28.62$, $MSE = 945.7$, $p < .01$, such that older observers performed less accurately overall (mean accuracy = 67.2%) than younger observers (mean accuracy = 88.6%). There was no difference between dichoptic and monoptic viewing conditions ($F < 1.5$), so further analyses collapsed across viewing conditions. The effect of SOA was also significant, $F(5, 90) = 7.60$, $MSE = 135.4$, $p < .01$. None of the two-way interactions were significant (Fs < 1.0).

Post hoc tests using combined data from the −100- and −50-ms SOA conditions as a baseline revealed that the performance of younger observers at the 0- and 50-ms SOA conditions was significantly worse than baseline (baseline = 92.4%; 0-ms SOA = 86.3%; 50-ms SOA = 79.6%); 0 ms, $F(1, 18) = 4.45$, $MSE = 105.3$, $p < .05$; 50 ms, $F(1, 18) = 11.12$, $MSE = 174.8$, $p < .01$. These were moderate to large effects (ds = 0.67 and 0.90, respectively). In addition, performance at the 50-ms SOA was significantly worse than the 0-ms SOA, $F(1, 18) = 4.51$, $MSE = 83.9$, $p < .05$. A similar pattern was found for older observers (baseline = 74.3%; 0-ms SOA = 64.5%; 50-ms SOA = 60.9%); 0 ms, $F(1, 18) = 11.02$, $MSE = 105.3$, $p < .01$; 50 ms, $F(1, 18) = 15.15$, $MSE = 174.8$, $p < .01$. These were moderate effects (ds = 0.65 and 0.73, respectively). The difference between the 0-ms and 50-ms SOA conditions was not significant ($F < 2.71$).

Discussion

In Experiment 2, both monoptically and dichoptically presented masks were used to test the hypothesis that the masking produced by the object mask in the older observers was due to central effects, namely object substitution. At the critical 50-ms SOA condition, older observers experienced an almost 14% decrease in accuracy compared to the baseline condition for both monoptic and dichoptic conditions. The monoptic viewing condition did not produce additional masking. This is consistent with the idea that the masking effect for all observers is postretinal in nature.

Object masking was also observed in the younger observers for both monoptic and dichoptic conditions. In previous work (Enns & Di Lollo, 1997), the object mask did not produce masking with younger observers, except under conditions of divided attention, which is consistent with the object-substitution hypothesis of Enns and Di Lollo. The monoptic condition was equivalent to the central-only object mask condition in Experiment 1, except that the target, mask, and background were reduced in luminance almost 4-fold in this experiment (from 82.5 cd/m^2 to 20.0 cd/m^2 for the background luminance) because of the experimental apparatus. It appears, as suggested previously, that a reduction in the spatiotemporal resolution of the target can interact with the process of masking via object substitution, either via the process of aging (older observers' far acuity [20/27.6] was significantly lower than that of younger observers [20/18.9]; $t(12) = 4.82$, $p < .05$) or

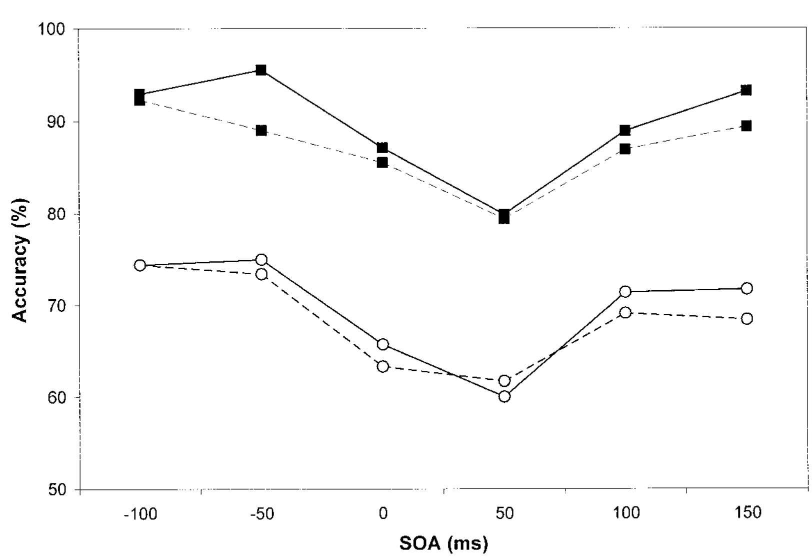

Figure 4. Masking data for Experiment 2. Data for the younger observers is on the top (black squares), and data for the older observers is on the bottom (open circles). Solid lines denote dichoptic presentation, and dashed lines denote monoptic presentation. SOA = stimulus onset asynchrony

through a change in display parameters. This hypothesis was tested further in Experiment 3.

Experiment 3

It is well known that aging can produce a number of decrements to sensory performance, including a reduction in contrast sensitivity (for a review, see Spear, 1993), and that these decrements interact with cognitive processes (Schneider & Pichora-Fuller, 2001). In the context of masking, a reduction in contrast would serve to reduce the *spatiotemporal resolution* of target information and thus leave it open to elimination through the process of object substitution. To test the hypothesis that masking effects in the older observers were due to reduced spatiotemporal resolution. We conducted Experiment 3 with a new set of younger observers, in which the contrast of the object-based mask and target was reduced to simulate age-related declines in spatiotemporal resolution. In this experiment, as with the Experiment 2, spatial attention was not manipulated. The object mask was presented over a range of SOAs with both mask and target presented to the central visual location only. However, a reduced contrast condition was added in which the target and mask were presented at a lower luminance than in the previous conditions. If spatiotemporal resolution of the stimuli is related to object-based masking, then the reduced contrast condition should produce masking, whereas the high-contrast condition should not. This would suggest that the performance of older observers is strongly influenced by the sensory quality of the encoded information.

Method

The stimuli and procedure were similar to those used in Experiment 2, except as noted below.

Participants

Eleven younger observers (3 men and 8 women; mean age = 21.2 years) participated for course credit. All observers had normal or corrected-to-normal far acuity (20/30 or better).

Materials

In this experiment, only the object mask was used and presented to the central visual field only. The target and mask were presented monoptically. The apparatus described in Experiment 2 was not used. Participants could not use background luminance as a cue for the type of upcoming trial, as the background luminance was always 66.7 cd/m^2. This luminance level was lower than in Experiments 1 and 2, to permit a smaller contrast ratio in the critical condition. The fixation stimulus was the same as in the above experiments and did not vary in luminance across trials. Two target–mask luminances were used, high contrast, with a luminance level of 0.60 cd/m^2, producing a contrast ratio of 0.98, and low contrast, with a luminance level of 49.3 cd/m^2, producing a contrast ratio of 0.15.

Procedure

There were two blocks of trials. In the first (practice) block of 24 trials, observers performed the target discrimination task without the mask. Both high and low contrast targets were used. The second block of 192 trials had six SOAs (−100, −50, 0, 50, 100, and 150 ms) and two target–mask luminances (high or low). There were 16 trials per condition (with 8 left targets and 8 right targets). The order of presentation was randomized.

Results

The data for Experiment 3 were analyzed with a three-way ANOVA and are presented in Figure 5. There was a significant effect of contrast, $F(1, 10) = 11.13$, $MSE = 183.2$, $p < .01$; SOA, $F(1, 50) = 10.99$, $MSE = 32.7$, $p < .01$; as well as a significant Contrast × SOA interaction, $F(1, 50) = 5.35$, $MSE = 31.3$, $p < .01$. On average, performance was worse on the low-contrast trials (87.3% correct) than on the high-contrast trials (95.2% correct). Post hoc analyses were performed to examine the effect of the mask at 0-ms and 50-ms SOAs for each contrast type. In these analyses, the data were compared with a baseline of combined data from the −100- and −50-ms SOA conditions in the second block. For the high-contrast case (baseline = 95.7% correct), there was no masking at 0-ms SOA (94.9% correct; $F < 1.0$), but there was a small masking effect ($d = 0.24$) at 50-ms SOA (92.6% correct),

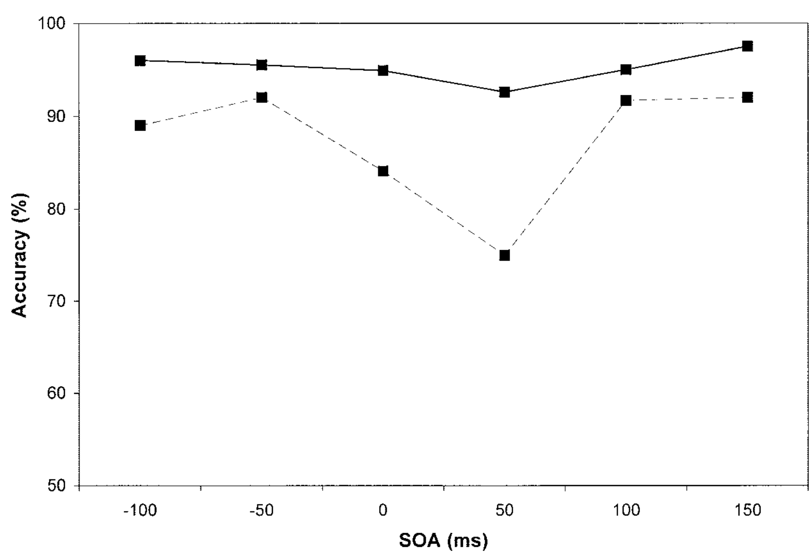

Figure 5. Masking data for Experiment 3 for the high-contrast condition (solid lines) and the low-contrast condition (dashed lines). SOA = stimulus onset asynchrony

$F(1, 10) = 6.88$, $MSE = 10.4$, $p < .05$. For the low-contrast case (baseline = 90.6% correct), there was a moderate masking effect ($d = 0.50$) at 0-ms SOA (84.1% correct), $F(1, 10) = 5.66$, $MSE = 55.3$, $p < .05$, and a large masking effect ($d = 0.82$) at 50-ms SOA (75.0% correct), $F(1, 10) = 33.53$, $MSE = 53.4$, $p < .01$. Post hoc comparisons of the contrast conditions across SOA revealed that only at the 50-ms SOA was performance in the low-contrast condition worse than in the high-contrast condition, $F(1, 10) = 49.53$, $MSE = 34.4$, $p < .01$. This was a large effect ($d = 0.96$).

Discussion

In Experiment 3, a group of younger observers performed the target discrimination task under conditions of focal attention with both low- and high-contrast conditions of the target and object masks in order to test the hypothesis that masking via object substitution for the older observers was influenced by reduced spatiotemporal resolution. If this were the case, then younger observers would experience similar declines in performance with reduced contrast stimuli. The data were clearly consistent with this hypothesis. The reduced contrast target and object masks resulted in a large decrease in detection accuracy over the high-contrast condition. (The small masking effect at 50-ms SOA in the high-contrast condition was probably due to the slightly reduced contrast in this condition compared with previous experiments.) Because this reduction occurred in the absence of a spread of spatial attention and in a sample of younger adults, the reduction in contrast is the only clear source of the effect.

It is useful to note that these results contradict the classic finding of Alpern (1953) which showed that the magnitude of metacontrast masking was directly related to stimulus intensity. The inhibitory interactions between parvocellular and magnocellular retinal ganglion cells underlying metacontrast masking increase in strength as a result of stimulus intensity, and thus produce greater masking. In masking via object substitution, masking occurs when the representation of target information encoded with low spatiotemporal resolution is eliminated by competing information. Thus, as stimulus intensity decreases, masking should increase because the target is more vulnerable to elimination. The pattern of results from Experiment 3 suggests that a reduction in sensory processes that degrade the quality of a target representation (due to age or via experimental manipulation) will leave target information vulnerable to postretinal masking effect, confirming the account of Enns and Di Lollo (1997; see also Di Lollo, Enns, & Rensink, 2000, for a more detailed version of this explanation).

General Discussion

The purpose of these experiments was to examine how attentional and sensory factors contribute to visual masking in older and younger adults, and to show that the interaction of these two effects produces a unique pattern of performance when considering the aging visual system. The critical findings of our experiments can be summarized as follows:

First, the source of the object masking was postretinal, presumably due to object substitution, as suggested by Enns and Di Lollo (1997). The object mask produced masking under dichoptic conditions (Experiment 2), and masking with this object increased with reduced target and mask contrast (Experiment 3), which is opposite to the pattern found in contour masking.

Second, younger and older observers had similar baseline performance for target discrimination under conditions of focused attention, but only the older adults showed masking when the object mask appeared at the same time as or up to 100 ms after the target when attention was focused. When attention was spread across a larger region of the display, baseline accuracy of the older observers decreased by 16%, whereas the baseline accuracy of younger observers was unchanged. In the absence of focused attention, older observers were unable to maintain a level of accuracy that made their ability to discriminate the target seem as intact as their younger counterparts. This indicates that older observers were probably using attention to increase the strength of a representation that was impoverished relative to their younger counterparts, resulting in a decrease in performance when the attentional gradient became less focused.

The third major finding confirms that the aging visual system is more vulnerable to attentional processes in masking because of a reduction in the spatiotemporal characteristics of the target provided by an aging eye, because similar effects can be found in “aged” younger observers. In Experiment 3, target contrast was reduced, and younger observers also experienced masking with the object mask under conditions of focused attention.

Previous research has suggested that visual masking in older adults is due to changes in postretinal processes. However, the nature of these processes has not been adequately explained. Typical explanations describe increased masking as due to a decline in *processing efficiency* of visual information with age (Hertzog, Williams, & Walsh, 1976; Kline & Birren, 1975; Speranza, Moraglia, & Schneider, 2001; Walsh, 1976). It is possible, therefore, that these declines in processing efficiency actually reflect age-related changes in attention that serve to increase masking via object substitution. This is only part of the explanation because, as the data from Experiment 3 demonstrate, this effect interacts with the initial strength of the visual stimulus. When spatiotemporal resolution was reduced, the object substitution effect occurred in younger observers under conditions of focal attention, whereas the effect previously required the spread of attention in younger observers. We presume that this is an analog to the poor performance with the object mask and focal attention for the older observers in Experiment 1, and that the older observers, because of declines in visual clarity with age, started with an impaired visual representation.

This effect illustrates that the interaction of two factors, peripheral and central processes, contribute to the effect of masking for both younger and older adults. However, older adults are particularly vulnerable to the effects of central processes in masking because peripheral changes make the information impoverished. These data serve as an important warning for researchers equating stimulus conditions for younger and older observers, because it requires careful control of both aspects of the visual stimulus and the attentional demands placed upon the observers. Under typical control conditions used in visual perception work with older adults, experimenters test for the ability of younger and older observers to see the stimuli under ideal conditions, and older and younger adults may appear to perform equally well. However, the two age groups may be performing equivalently using different processes. For the younger adults, the visual stimulus may have a suprathreshold representation that is relatively immune to the effects of competing stimuli or increased attentional demands. For example, in our data, the younger observers were able to discriminate between targets despite the presence of the object mask when attention was focused and when attention was distributed, except at critical SOAs. Performance of older observers under ideal conditions may appear to be equivalent to that of younger observers, but only by virtue of attentional enhancement of an impoverished visual representation. In this study, the older observers were only able to maintain a similar level of performance to the younger observers when attention was focused.

What remains to be determined are the relative contributions of these and other factors to visual perception in older and younger adults, as well as the level of interaction among the various factors. We examined only two factors: attention and stimulus contrast. Other processes may include sensory functions, such as acuity; higher order cognitive functions, such as the classification and categorization stages of visual processing (Di Lollo et al., 1982); or disease-related decrements to cortical function that can accompany age (Gilmore, 1995; Gilmore, Thomas, Klitz, Persanyi, & Tomsak, 1996).

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