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Aging, perception, and visual short-term memory for luminance-defined form

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Summary

The sensory, perceptual, and visual short-term memory (VSTM) capacity of young and older observers for processing luminance-defined shape information was assessed in a series of experiments. The following were assessed: each individual's threshold necessary to detect a square from its background as measured by luminance thresholds; the capacity for making simultaneous size discriminations when compensating for individual differences in sensory input; the capacity for making sequential size discriminations; and the capacity for remembering size differences over time. The results show a selective deficit for simultaneous perceptual processing for older subjects, which cannot be attributed to differences in sensory input, task difficulty, interhemispheric transfer, or VSTM. © 2000 The College of Optometrists. Published by Elsevier Science Ltd. All rights reserved.

General introduction

The present study examines the effect of normal aging on the capacity to detect, discriminate and memorize visual information using a bottom–up "stimulus-driven" approach. Several lines of evidence converge to suggest that there are overall changes in the processing of visual information with increasing age. For example, there is a change or reduction in visual attention with increasing age (Ball *et al.*, 1993; Steinman *et al.*, 1994); the elderly exhibit processing deficits for a number of basic visual functions (for reviews, see Pitts, 1982; Kline and Schieber, 1985; Fozard, 1990; Owsley and Sloane, 1990; Werner *et al.*, 1990; Kline, 1991; Spear, 1993) and other cognitive and motor factors are also compromised by aging (Birren, 1965; Waugh and Barr, 1980; Salthouse, 1994). Also, many studies have demonstrated anatomical psychophysical and electrophysiological deficits with aging (Pitts, 1982; Kline and Schieber, 1985; Werner *et al.*, 1990; Kline, 1991; Ordy *et al.*, 1991; Owsley and Burton, 1991; Sturr and Hannon, 1991; Spear, 1993).

Recent work has attempted to link processing at the sensory-perceptual level and visual short-term memory (VSTM). Vogels and Orban (1986) studied VSTM for oriented lines over durations of up to 10 s and found that there was a decrease in performance with increasing interstimulus interval (ISI). Regan (1985) showed that spatial frequency information was well preserved up to 20 s. Magnussen and colleagues (Magnussen *et al.*, 1990, 1991) confirmed Regan's original finding and extended this for a 30-s period. They also tested parallel and orthogonal gratings, found good retention, and concluded that spatial discrimination and spatial memory were based on the same underlying processes. Masking experiments showed that masking does not interfere with stored information unless the mask is substantially different from the stored information (Magnussen *et al.*, 1991). Subsequent work demonstrated that masking velocity information produced similar results (Magnussen and Greenlee, 1992). Finally, neurophysiological work on the monkey suggests that information stored in VSTM is coded by the same neuronal assembly as that responsible for visual processing (Mayashita and Chang, 1988).

In the present investigation, the detection, simultaneous

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size discrimination, and VSTM for luminance-defined squares was assessed in young and older observers in five experiments. A special emphasis was placed on appropriate control of the stimulus parameters so that any differences in performance between the young and older groups were not a consequence of individual differences in sensory input or other factors such as reaction time and task-related differences in cognitive load. The purpose of the study was to determine whether performance at the sensory, perceptual, and VSTM processing levels was affected by aging in a similar fashion, while controlling for individual sensory input (luminance intensity) for the perceptual and VSTM stages.

General method

Subjects

Thirty-two subjects participated in Experiments 1–3. Seventeen observers were younger normal adults (4 males and 13 females) ranging in age from 20 to 36 years with a mean age of 24.3 years, a median of 22.0 years and a standard deviation of 4.48 years. These volunteers were recruited from the student body of the University, and everyone was tested after their ocular health had been determined with a complete visual examination [refraction (best corrected visual acuity), ophthalmoscopy, biomicroscopy, tonometry, stereoscopy, central and peripheral field of vision]. The remaining 15 subjects were older adults (5 males and 10 females) ranging in age from 64 to 75 years with a mean of 69.1 years, a median 69.0 years and a standard deviation of 3.06 years. All older subjects were recruited from a private optometry practice and were tested after their ocular health had been determined with a complete visual examination. During testing, subjects wore their best refractive correction for far distance. The best corrected visual acuity for the older subjects was 6/7.5 or better and 6/6 or better for the young observers. All subjects had good ocular and general health based on their medical history.

Apparatus and stimuli

A Macintosh Quadra 840AV computer interfaced with a Mitsubishi Diamond Pro series high resolution monitor [1152 pixels in width (39.5 cm) × 870 pixels in height (29.3 cm)] composed of a standard P22 RGB phosphor was used to present stimuli and collect data. The calibration procedures have been described previously in detail (Faubert, 1991). Essentially, the gun outputs were made linear up to 99% of their capacity by using appropriate calibrating procedures which assume no independence of the guns. The monitor was viewed binocularly at a distance of 3 m. The monitor was the only source of light and the mean luminance of the random-dot background was 20 cd/m^2, which corresponds to the space-average luminance of the dark and light areas together.

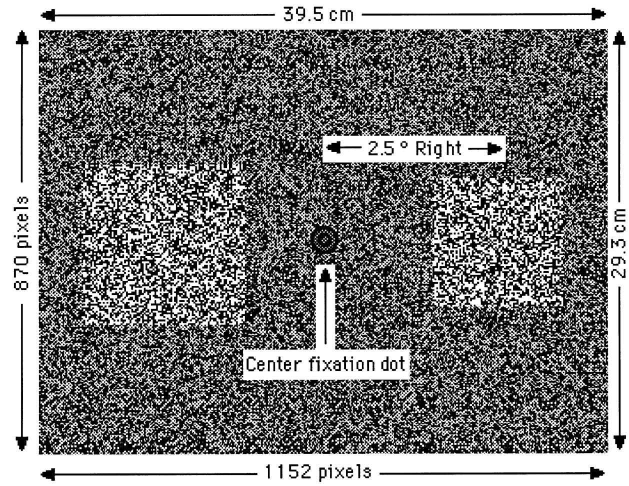

Figure 1. General configuration of the stimuli used in the experiments. The luminance contrast is exaggerated for illustrative purposes. In Experiment 1 the task was to determine on which side a single target was presented. In Experiment 2 the contrast was adjusted at a 0.5 log-unit suprathreshold level for each individual based on the results of Experiment 1. The task was to determine on which side the largest square was presented. In Experiment 3, the task was to determine whether the largest square was presented in the first or the second presentation.

The stimuli for all the experiments had the same general appearance (e.g. *Figure 1*). The entire screen was filled with a random-dot pattern of dark and gray dots giving a textured appearance. This type of display is often used so that it is possible to isolate specific visual attributes which define the stimulus from the background. For instance, if we want to define a stimulus by stereoscopic cues, it is possible to camouflage the target into random noise so that it is impossible to see the target unless the correlated steroscopic signal is fused to produce the impression of a solid object. A similar process is used to isolate other attributes such as motion and texture. Because our intent is to evaluate the effect of aging on the capacity to perceive and remember stimuli defined by a number of visual attributes, we decided to use the same general random-dot background for our initial luminance-defined stimuli experiments. Specifically, in order to distinguish our stimulus from its background, we can change the contrast between the illuminated dots which are contained within the area defining the target as compared to the illuminated dots which compose the background (see *Figure 1*). For our experiments, the individual dot size used was 24 s of arc and the density was always maintained at 50%. This means that there was an equal number of dark and gray dots everywhere on the screen. A small red dot served as a fixation point and remained on in the center of the screen throughout all trials.

General procedure

The subjects were positioned on a chin and forehead rest and fixated the central red spot throughout all trials. The experimenter constantly reminded subjects to maintain fixation on the red spot and observed the subject's eyes throughout all trials. Fixation failures were extremely rare and they did not differ by condition and/or by age group. If a fixation loss was observed by the experimenter, the trial was repeated at the end of the each experiment. The subjects were not told that the trial was being repeated and no feedback was given after each response. Once the stimuli were presented, no time restriction was imposed for the subject's response. The next trial was initiated immediately after the subject's response. A two-alternative forced choice (2AFC) constant stimuli procedure with a minimum of seven levels was used for all five experiments. Three additional levels were automatically added for some of the observers who did not reach 90% of correct responses. Each level contained 20 trials for a minimum of 140 trials per experiment. Experiments 1, 2 and 5 consisted of spatial 2AFC tasks while Experiments 3 and 4 were temporal 2AFC procedures. The specific tasks for each experiment are described below. The older observers responded orally and the experimenter pressed the key according to their oral responses. Our pilot data demonstrated no differences in thresholds for the younger observers when they responded orally or by pressing the keys themselves, therefore the younger observers responded by pressing the corresponding key. Thresholds were established at a 75% correct response level using a bootstrap procedure (Foster and Bischof, 1991). The stimulus duration was 1 s for all trials.

The subjects were shown the display and were given practice trials (10–20) for each testing condition in order to ensure that each observer understood the task. In Experiments 2–5, the subjects had the choice to take a rest period at any time. The testing time required for Experiments 1–3 combined (generally done in the same session) was between 75 and 90 min in total. The session for Experiment 1 lasted approximately 5 min. Experiment 2 lasted approximately 10 min and Experiment 3 lasted approximately 60–75 min.

Experiment 1

In the first experiment, we established the effect of aging on luminance detection thresholds for square shapes. The computer randomly presented the squares to the right or left of the fixation spot and the subject responded accordingly, i.e. the subject had to respond whether the square was presented to the left, or the right, of fixation. Luminance detection thresholds were established for a 1° square target centered at 2.5° to the left or right of foveal fixation with a 2AFC constant stimuli procedure. A minimum of seven different luminance levels were used ranging from 0.35 to 2.70 cd/m^2, which corresponds to 0.0016–0.1350 in Weber fractions ($\Delta L/L$). These levels were presented in pseudo-random order by the computer and they were established by increasing white area luminance. The results of Experiment 1 were used to establish a level of equivalent sensory input for each observer in following experiments.

Experiment 2

The second experiment determined the effect of aging on the capacity to discriminate the difference in size of two simultaneously presented squares (stimulus onset asynchrony (SOA) of 0 s). The squares were presented simultaneously for a period of 1 s. On a given trial, the computer randomly presented the reference and target squares of different sizes to the left and right of the fixation. A minimum of seven different sizes of the comparison stimuli were used. The difference in size as compared to the reference target (1°) ranged from a minimum of 24 s of arc to 168 s of arc and up to a maximum of 240 s of arc (for additional levels) resulting in Weber fractions ($\Delta a/a$) between 0.013 and 0.138. The size of the target square was always increased symmetrically, that is, all four sides increased by 24 s of arc for the minimal size step so that the squares could not be discriminated on the basis of shape differences. The reference square was the same constant size on each trial and was always the smallest square. The task was to determine on which side of the fixation spot the larger (target) square was positioned. The squares were presented at 0.5 log-unit luminance above the individual thresholds previously determined in Experiment 1 in order to ensure equivalent sensory input for all observers. The spatial resolution of the system was 24 s of arc (1 pixel at 3 m). An example of this stimulus configuration is presented in *Figure 1*.

Experiment 3

In the third experiment, we assessed the effect of aging on the capacity to retain size information in VSTM for suprathreshold luminance-defined squares. As in Experiment 2, a 0.5 log-unit suprathreshold condition based on the results of Experiment 1 was calculated for each of the 32 observers. This value was used throughout the experimental conditions which included 1, 3 and 10-s ISIs between the first and second presented squares. The order of the ISIs was randomized across observers. During the retention interval of 1, 3 or 10 s, the random dot background was presented with the central fixation dot. The range and sizes of the reference and target squares were the same as in Experiment 2. The task was to determine which square was the largest, the one presented first or second. The different sizes and their position (left/right) were presented randomly by the computer. The second square was always presented on the same side as the initial square in order to avoid spatial uncertainty.

Results

Experiment 1. The results of Experiment 1 are presented in *Figure 2(a)* as Weber fractions. The Weber fraction is the relative difference of a given parameter necessary to discriminate a stimulus from its baseline value (reference stimulus). In this case it is the luminance thresholds (ΔL) divided by the baseline luminance (L). A student t-test for independent measures indicates a significant difference in luminance thresholds for the two groups ($t = -5.371$, $p < 0.001$).

Experiment 2. The data of Experiment 2 are presented in *Figure 2(b)*. *Figure 2(b)* shows the mean discrimination thresholds (smallest differences in sizes between the squares that can be discriminated 75% of the time) as Weber fractions for the young and older groups. In the present case, the size of the square is defined as the area in seconds of arc squared (3600×3600 for a 1° target). If the threshold value to discriminate the target from the standard involves increasing each side of the square by 40 s of arc, for example, then the Weber fraction is calculated by the following formula:

Weber fraction $= \Delta a/a$

where $a = (3600 \times 3600)$ and $\Delta a = (3640 \times 3640) - a$.

The data are quite clear and demonstrate that there is a difference between the older and younger groups for making simultaneous size discriminations. A student t-test for independent measures indicates a significant difference in simultaneous size discrimination thresholds for the two groups ($t = -4.967$, $p < 0.001$).

Experiment 3. The data of Experiment 3 are presented in *Figure 2(c)*. The data are represented as mean size discrimination thresholds (Weber fractions) as a function of ISI condition for the young and older groups. A 2×3 between-within repeated measures ANOVA was calculated and the results show no statistically significant difference for either the group ($F < 1$) or ISI conditions ($F = 2.31$, $p > 0.1$). No significant interaction between the group by ISI conditions was found ($F < 1$).

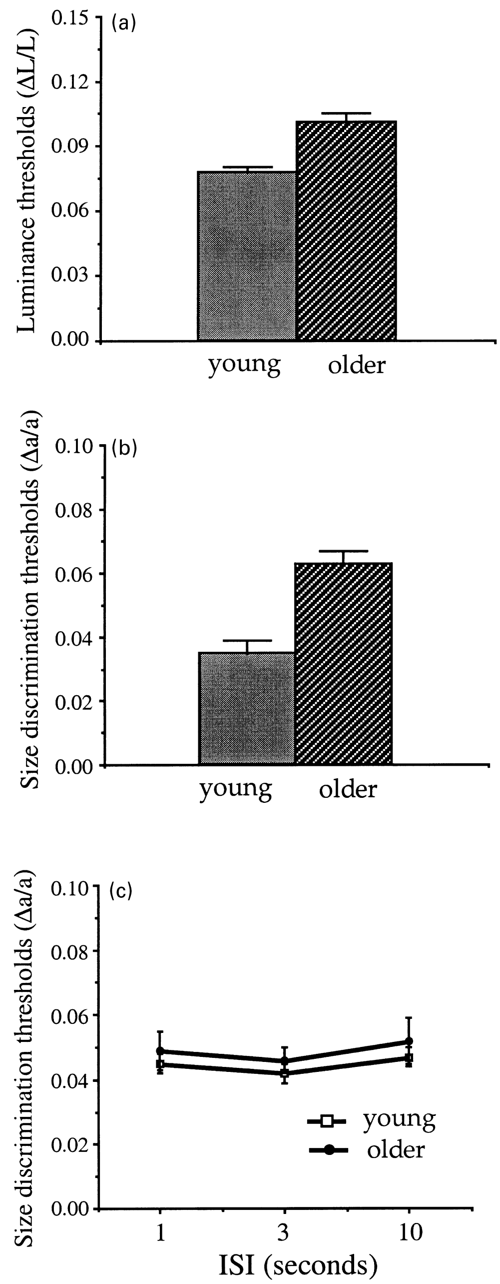

Figure 2. (a) Mean luminance thresholds presented as Weber fractions for young and older groups obtained in Experiment 1. Error bars indicate standard errors of the mean for each group. (b) Mean size discrimination thresholds obtained in Experiment 2 represented as Weber fractions for the young and older groups. (c) Mean size discrimination thresholds obtained in Experiment 3 as a function of ISI represented as Weber fractions for the young and older groups. The young subjects are represented by open squares and the older subjects by closed circles.

Discussion

The results of Experiment 1 indicate an age-related loss in processing sensory information with age for luminance-defined shape information. This is consistent with previous reports which found a loss of spatial contrast sensitivity for older groups (Elliott; 1987; Greene and Madden, 1987; Owsley and Sloane, 1987, 1990; Crassini *et al.*, 1988; Sloane *et al.*, 1988; Elliott *et al.*, 1990; Owsley and Burton, 1991; Burton *et al.*, 1993). These studies have generally tested the contrast sensitivity of subjects using sinusoidal gratings and most of them have found sensitivity losses for medium to high spatial frequencies (although some have also found losses for lower spatial frequencies). A random-dot stimulus such as the one used in our experiments includes components from a broad band of spatial frequencies, including medium to high spatial frequencies. Therefore, it is not surprising that we also obtain a sensitivity loss with aging with these stimuli.

The results of Experiment 2 show that there is a specific loss with age for simultaneous size discriminations, whereas the results of Experiment 3 indicate no significant effect of age on the VSTM storage of sequentially presented stimuli. It is important to note that the individual differences in luminance detection thresholds were compensated for in Experiments 2 and 3. Therefore, the difference observed in Experiment 2 between groups truly represents a decrement in perceptual discriminations when the targets are presented simultaneously. The fact that there is no effect of age on VSTM is also an interesting finding. It implies that, although there is a limited processing capacity for targets when they are presented simultaneously, there is no evidence of such reduced processing capacity when the targets are maintained in VSTM even for conditions where the size information has to be stored for 10 s!

Although these results are interesting and potentially important, there are some weaknesses in this study which must be addressed before we can conclude that there is a selective effect of aging on the capacity to discriminate simultaneously presented visual stimuli. The major weakness resides in the different spatial configurations of Experiments 2 and 3. It is possible, for instance, that the VSTM information does not degrade with time because the stimulus input is too easy to discriminate. Further, because the reference and the target stimuli are presented sequentially in Experiment 3 the overall presentation time is twice as long (1 s for the reference and 1 s for the target for a total of 2 s) as in Experiment 2 (1 s for both targets), which may account for the difference in performance with the tasks.

For these reasons we set out to conduct a fourth experiment where the spatial configuration was very similar to Experiment 2. In this case, two squares were simultaneously presented and, after a given ISI (1, 3 or 10 s), a third square was presented in the center. The task was to determine whether this square was the same size as the one to left or the right in the initial presentation. This represents a delayed matching task. The observer must first discriminate the two targets (like Experiment 2) and then retain this difference in memory for later comparison (like Experiment 3).

Experiment 4

Subjects. A subgroup of 10 subjects from the first three experiments participated in this experiment: 8 females and 2 males. Five observers were younger normal adults (5 females) ranging in age from 20 to 25 years with a mean of 22.6 years, a median of 22.0 years and a standard deviation of 2.30 years. The remaining 5 subjects were older adults (2 males and 3 females) ranging in age from 66 to 75 years with a mean of 69.8 years, a median of 69.0 years and a standard deviation of 3.27 years.

Procedure. As in Experiments 2 and 3, a 0.5 log-unit suprathreshold condition based on the results of Experiment 1 was calculated for each of the 10 observers. This value was used throughout the experimental conditions, which included 1, 3 and 10-s delays between the two simultaneously presented squares and the third square presented later (ISIs). A minimum of seven different sizes of the comparison stimuli were used. The difference in size as compared to the reference target (3600 s of arc) ranged from a minimum of 72 s of arc to 480 s of arc and up to a maximum of 672 s of arc (for additional levels) resulting in Weber fractions ($\Delta a/a$) between 0.040 and 0.408. This experiment consisted of a combination of procedures used in Experiments 2 and 3. In a given trial, two squares were presented simultaneously (exactly like Experiment 2). After a given ISI (like Experiment 3), a third square was now presented in the center of the screen to avoid any local spatial cues. Prior to presenting the third square (1 s), the central red fixation spot disappeared and the subjects were told to maintain their fixation in the center. The task was to determine whether the square shown in the center was the same size as the square presented previously to the left or the right side of the fixation dot. A schematic of this procedure is presented in *Figure 3*.

Results. The results of Experiment 4 are represented in *Figure 4*. The results show that older and younger groups differ for the VSTM conditions of 1, 3 and 10 s. This is evidenced by the fact that we obtained a simple main effect for the grouping condition ($F = 9.227$, $p < 0.02$). We also obtained a significant ISI effect ($F = 9.164$, $p = 0.002$) but no significant group by ISI interaction ($F = 1.812$, $p = 0.2$).

Discussion. The results of Experiment 4 show that the simultaneous presentation deficit in the older population is apparent even when the simultaneous targets were compared in memory. Furthermore, the deficit did not increase or decrease with increasing ISI conditions, implying that VSTM itself is not affected. If there was a VSTM deficit with aging, the results should get worse with increasing ISI. The results of Experiment 4 show that there is no ISI by group interaction. In fact, when the results of Experiments 2 and 4 are directly compared we find that the magnitude of the difference remains approximately the same. In general, the individual data show the same trend except for one subject who appeared to get worse at the longest ISI. Therefore, the deficit observed in Experiment 4 is the result of the initial simultaneous configuration of the stimulus, and it represents a true perceptual deficit and not a VSTM deficit.

There remains one further possibility to explain the different results of Experiments 2 and 4 versus the results of Experiment 3. In Experiments 2 and 4, the judgement is made between squares that are presented at two different

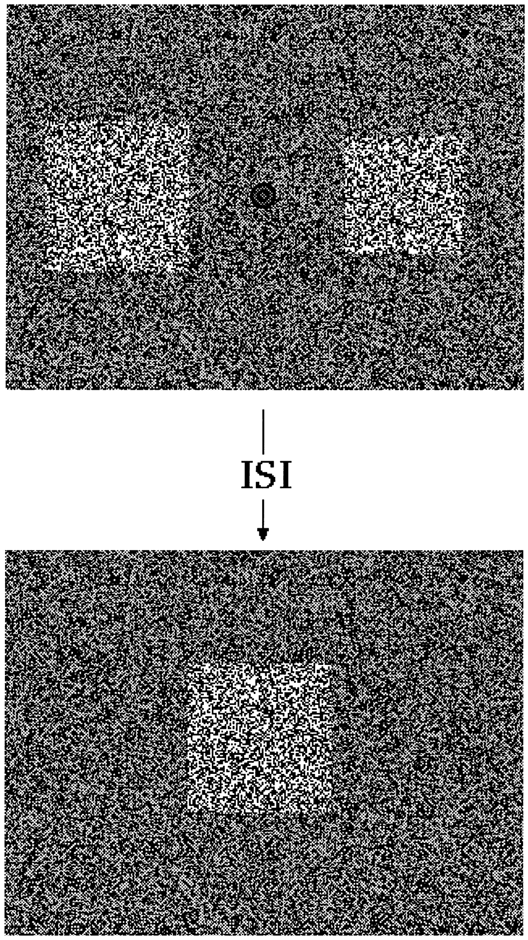

Figure 3. Example of stimuli used in Experiment 4. The luminance was adjusted at a 0.5 log-unit suprathreshold level for each individual based on the results of Experiment 1. The task was to determine whether the second presented square resembled the left or right initially presented simultaneous squares.

hemifields from the vertical meridian. This means that to make this judgement the information from one hemifield (one side of the cortex) must be compared with the information from the other hemifield (other side of cortex) simultaneously, implying an interhemispheric transfer and larger processing requirements. To eliminate the possibility that the difference in the results was due to this interhemispheric transfer, we conducted a fifth experiment that included conditions where the simultaneous judgements were within the same hemisphere.

Experiment 5

Subjects. Twenty subjects participated in this experiment: 9 of the 10 observers who participated in Experiment 4 also participated in this experiment (4 young and 5 older observers). Eleven observers were younger normal adults ranging in age from 19 to 31 years with a mean of 23.6 years, a median of 22.0 years and a standard deviation of 6.6 years. The remaining 9 subjects were older adults ranging in age from 67 to 77 years with a mean of 70.4 years, a median of 69.0 years and a standard deviation of 3.68 years.

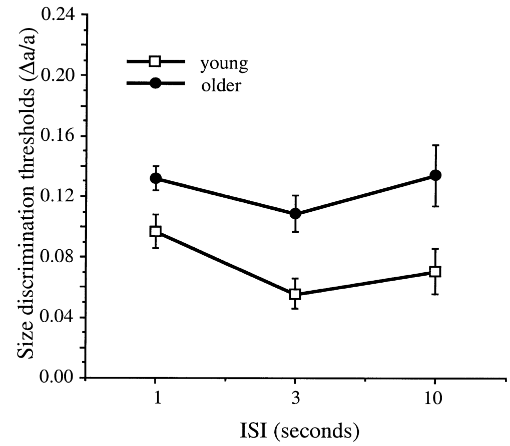

Figure 4. Mean size discrimination thresholds obtained in Experiment 4 as a function of ISI represented as Weber fractions for the young and older groups. The young subjects are represented by open squares and the older subjects by closed circles. Error bars indicate standard errors of the mean for each group.

Procedure. The procedures were the same as in the previous experiments with regards to establishing luminance thresholds and presenting the stimuli at suprathreshold conditions for the simultaneous size discriminations. The important difference is that, in addition to the simultaneous size discrimination for horizontally positioned stimuli (e.g. Experiment 2), we also assessed three other conditions of simultaneous size discriminations. The three conditions consisted in presenting pairs of vertically aligned squares above and below the horizontal midline either at the foveal axis (where parts of the squares would overlap the left and right visual hemifields) in the left visual hemifield or in the right visual hemifield. Other than the spatial location, all other procedures were identical to those of Experiment 2. The total testing time for all conditions was between 20 and 30 min.

Results. The results for the four different simultaneous discrimination threshold conditions are presented in *Figure 5*. A 2×4 repeated measures ANOVA was calculated and reveals a significant main effect between the young and older groups ($F = 5.097$, $p < 0.04$) but no significant main effect of stimulus configuration ($F = 1.6$, $p = 0.2$). Further, no significant interaction between age and stimulus configuration was found ($F < 1$).

Discussion. The results of Experiment 5 are clear and illustrate two main points. First, the deficit for simultaneous

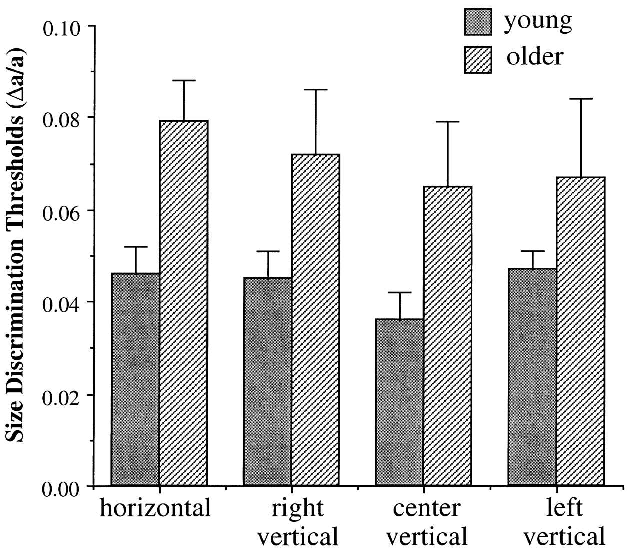

Figure 5. Mean size discrimination thresholds obtained in Experiment 5 as a function of spatial configuration of the stimulus display represented as Weber fractions for the young and older groups. Error bars indicate standard errors of the mean.

perceptual processing, as assessed by size discrimination, is selectively affected by aging confirming the results of Experiments 2 and 4. Secondly, the results clearly show that the deficit for making simultaneous size discriminations for horizontally placed squares observed in Experiments 2 and 4 is not caused by interhemispheric transfer changes with aging. In fact, the simultaneous discrimination deficit as a function of age was observed in all stimulus configuration conditions as evidenced by a lack of age by stimulus configuration interaction.

General discussion and conclusions

In the series of experiments presented here, there are three main processes involved: the initial sensory detection, simultaneous discrimination, and VSTM. Aging affects the detection process, but also effects the discrimination system but only when stimuli are presented simultaneously. This is evidenced by the fact that the older subjects had no relative losses as compared to younger observers when size discrimination was based on a temporal forced-choice discrimination procedure. The cause of this specific loss to simultaneous discriminations with aging is unclear. It could be explained by a reduced capacity for spatial attention. This explanation, however, is not totally satisfactory. For instance, the area of stimulation in our experiments is limited, in general, to the central 6° of the central visual field which is well within a functional useful field of view (UFOV) for our presentation time of 1 s (Ball *et al.*, 1993). There was also no stimulus uncertainty in our simultaneous discrimination task. Furthermore, the results of Experiment 4 show that it is the deficit in processing simultaneous information which is carried over into VSTM, and not VSTM in itself that is affected by aging. In a recent study using a very different methodology and task, Korsnes and Magnussen (1996) have reached similar conclusions with regard to the effect of aging, i.e. they concluded that it was discrimination performance rather than the storage mechanisms that was affected by aging. In a task more related to our own experiments, Latham and Barrett (1998) have shown that judgements for spatial interval discriminations with a 500 ms ISI were unaffected with aging. Therefore, it appears that the results across studies are consistent when spatial judgements are performed with temporal intervals (STM) in that these judgements are robust to the effect of age.

An important distinction must be made regarding our results and those of "simultaneous judgement" studies (Craik, 1977; Craik and Simon, 1980). Those studies have shown an aging effect when subjects are required to divide their attention between two concurrent tasks ("simultaneous judgements"). In our results, the subjects were required to make a single size judgement from simultaneously presented stimuli.

In a recent study, Lages and Treisman (1998) have suggested that what is maintained in STM is not the spatial information per se but, rather, it is a decision criterion which is stored. In other words, observers keep an average reference prototype of the spatial information in memory to which they can compare subsequent information. Whether it is this type of criterion reference or it is actual spatial comparisons which are made in time by our observers, the fact remains that comparing spatial information over time in STM is not affected by the normal aging process.

Our present findings reflect the relative importance of age on the detection, discrimination, and storage of luminance-defined form information under specific viewing conditions. They also give us insights on how the normal visual system is structured for processing visual information. We know that there are bottom–up and top–down interactions in the perception of simple visual stimuli (Fauber and von Grünau, 1995). It may be the case that a phenomenon such as attentional priming could compensate for the deficits observed in the present studies by modulating neural signals reduced by some cell loss or malfunction. Another interesting question is whether practice can reduce the relative difference between young and older observers seen in our simultaneous processing deficit tasks. Such a diminished difference between groups due to practice effects has been demonstrated in the UFOV experiments (Ball *et al.*, 1993). This would tell us how "automatic" the visual processing required in the present experiments can become. Presumably, the more automatic a response the less neurons are required to process the information (or it is possible that there are the same number of neurons with stronger connections). Thus, according to the logic presented above, the processing of more automatic tasks should be less affected by aging.

Finally, much work is still required to determine the effect of aging on visual processing. We believe that it is important to bridge the gap between the sensory and other processing levels related to the aging process and our present study is a step in that direction.

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