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# Aging effects on intra- and inter-attribute spatial frequency information for luminance, color, and working memory

Jocelyn Faubert \*, Anne Bellefeuille

Département de psychologie et École d'optométrie, Université de Montréal, 3744 Jean-Brillant, Montreal, Que., Canada H3C 1P1 Received 2 September 1999; received in revised form 15 February 2001

### Abstract

Visual working memory (VWM) for spatial frequency information was assessed in both young and older observers. In the first experiment we assessed the effect of a memory mask on a VWM task. We found no effect of mask on retention for either the young or older groups. This argues against the 'inhibition' hypothesis of aging in regards to visual processing, which suggests that the elderly should have difficulty to inhibit irrelevant information. We conclude that the suggestion of an inefficient inhibition process in aging derived from evidence obtained for higher-level WM tasks cannot be generalized to the discrimination of basic patterns in VWM. The second experiment focused on processing resources within VWM by assessing VWM for intra-attribute (color or luminance), and inter-attribute (color and luminance)-defined spatial frequency information. Results show that retention of spatial frequency information in VWM is robust for both the younger and older group regardless of the defining attribute. Thresholds were significantly higher in the inter-attribute condition, indicating increased processing demands for this task and suggesting that these attributes are initially processed in parallel. Older observers showed higher discrimination thresholds than young observers for all conditions indicating a deficit in perceptual abilities rather than in VWM for basic stimuli. The difference in thresholds for the older group was highest in the inter-attribute condition suggesting that older observers show more deficits on visual tasks with increased processing demands. © 2002 Elsevier Science Ltd. All rights reserved.

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# 1. Introduction

There has been a recent growing interest in shortterm or working memory (WM), a brain system that provides temporary storage of information and manipulates this information to perform cognitive tasks. WM, as described by Baddeley (1986), has a sensory storage buffer in which information can be held for a short period of time and a central executive system responsible for performing computations and transformations. Evidence suggests the existence of multiple WM buffers: verbal, spatial, visual, and probably one for every sensory input (see Jonides & Smith, 1997 for review).

#### 1.1. Visual working memory

Studies on WM have traditionally focused on verbal and visuospatial material. Recently, researchers have examined WM for purely visual material, thus providing a link between WM and basic visual processing by examining how a stimulus is maintained in memory when it is defined by a simple visual attribute. These studies used discrimination thresholds (DT) at varying interstimulus intervals (ISI). The assumption is that the first stimulus has to be stored, maintained, and retrieved in order to compare it to the second one (Regan, 1985). Studies have found that luminance-defined spatial frequency and velocity information are well preserved in visual working memory (VWM) for periods up to 10 s or more (Magnussen & Greenlee, 1992; Magnussen, Greenlee, Asplund, & Dyrnes, 1990; Regan, 1985). In contrast, oriented lines, contrast information, and vernier offsets show a slight decay for such time intervals (Fahle & Harris, 1992; Lee & Harris, 1996; Vogel & Orban, 1986). Thus, it appears that some visual attributes

<sup>&</sup>lt;sup>\*</sup>Corresponding author. Tel.: +1-514-343-7289; fax: +1-514-343-2382.

E-mail address: jocelyn.faubert@umontreal.ca (J. Faubert).

produce a more robust memory trace than others. Hole (1996) proposes that memory for simple stimuli (e.g. spatial frequency) might be based on some lower level mechanism than that of the more complex stimuli and thus be more resistant to the passage of time.

Magnussen, Greenlee, Asplund, and Dyrnes (1991) described the disruption of VWM for spatial frequency with the presentation of a memory mask during the retention interval. Higher DT were obtained when the spatial frequency of the mask differed from the reference grating by 1–1.5 octaves and greater. DTs were equal when the mask and reference grating were of similar spatial frequency. Orientation, duration, and presentation time of the mask had no additional effects on threshold. Magnussen et al. (1991) interpreted their results as strong suggestion that VWM shared the same representation as sensory information. Bennett and Cortese (1996) confirmed the finding of Magnussen et al. (1991) and further reported that the effect of the mask was based on distal and not proximal frequency.

There is evidence that there are some independent, parallel, special-purpose memory stores, each devoted to a particular attribute of a visual stimulus. For example, Magnussen and colleagues (Magnussen, Greenlee, & Thomas, 1996) showed subjects a spatial frequency grating of a given contrast and asked to compare it to another grating that differed either in frequency or in contrast. In the single attribute condition, subjects were told along which dimension the second stimulus would vary. Subjects were then just attending to one attribute. In the double attribute condition, subjects were not informed along which dimension the second stimulus would differ, thus, requiring an encoding of both attributes. When taking into account the increased threshold predicted by the uncertainty case, subjects performed as well when attending to a single attribute or the two attributes combined, suggesting independent parallel VWM processing of contrast and spatial frequency.

# 1.2. Visual attributes: color and luminance

Contours of visual information can be defined by one or a combination of several surface attributes, such as luminance, color, motion, texture and binocular disparity. Luminance and color are considered to be first order characteristics because they are sufficient to generate a contour. The other attributes as considered second order characteristics since they are constructed from spatial, temporal and interocular information, coded from color or luminance (Cavanagh, 1988). Luminance information is believed to be more efficient in providing contour information than color or other attributes (Gregory, 1977).

Psychophysical evidence indicates that attributes are processed independently. For example, after adapting to a luminance defined grating, the spatial frequency of a color defined grating does not appear to change and vice versa (Favreau & Cavanagh, 1981), indicating that the visual system codes color and luminance information separately for spatial frequency analysis. Although information about different attributes appears to be coded separately, it seems to be integrated at a common site (e.g. Rivest & Cavanagh, 1996; Rivest, Boutet, & Intriligator, 1997). For example, the position of a contour defined by one attribute influenced the position of another contour defined by a different attribute, suggesting that the information from the different attributes united at a common site to provide position information (Rivest & Cavanagh, 1996).

#### 1.3. Aging and visual working memory

There is much evidence for overall changes in the processing of visual information with increasing age. For example, there is a change or reduction in visual attention (Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Steinman, Steinman, Trick, & Lehmkuhle, 1994). Deficits are found for a number of basic visual functions (for reviews see Kline & Scialfa, 1996; Owsley & Sloane, 1988; Spear, 1993; Werner, Peterzell, & Scheetz, 1990). Anatomical, psychophysical, and electrophysiological deficits have also been found in the aging visual system (Kline & Scialfa, 1996; Ordy, Wengenack, & Dunlap, 1991; Owsley & Sloane, 1988; Pitts, 1982; Spear, 1993; Sturr & Hannon, 1991; Werner et al., 1990).

It is generally agreed that older individuals experience difficulties with WM (see Craik & Jennings, 1992; Van der Linden & Hupert, 1994 for reviews). Factors that have been proposed to account for a reduction of WM in aging include a reduction of processing resources, slower processing abilities, and increased difficulty to inhibit irrelevant information (Van der Linden & Hupert, 1994).

To date, studies on aging and VWM for simple visual attributes report no loss of information for vernier acuity (Fahle & Daum, 1997), spatial interval (Latham & Barrett, 1998), luminance defined squares (Sara & Faubert, 2000) and luminance defined spatial frequency information (McIntosh et al., 1999). There is, however, in some studies, an elevation in DT for older observers, suggesting a perceptual processing deficit rather than a deficit in VWM (Sara & Faubert, 2000).

In the present study, we wanted to assess whether a memory mask and aging would interact in the retention of spatial information in VWM. We also wanted to explore VWM and processing resources in young and older observers by using different attributes to define spatial frequency information. The first experiment examined the effect of a memory mask on VWM for spatial frequency information in a group of older adults. Special emphasis was placed on appropriate control of the stimulus parameters so that any differences in performance between young and older groups were not a consequence of individual differences in sensory input or other factors such as reaction time. The retention of spatial frequency was measured in VWM using DT. In the second experiment, the stimuli to be compared were defined by the same attribute (color or luminance) or by different attributes, (inter-attribute), (color and luminance) for ISIs of 1 and 10 s.

# 2. Experiment 1: Discrimination thresholds with an oriented memory masker in working memory

It is possible that the lack of aging effects on VWM shown in previous studies (e.g. McIntosh et al., 1999; Sara & Faubert, 2000) are due to the low-level nature of spatial frequency and luminance processing. One way to disrupt this processing is by using masking stimuli during the retention task (Magnussen et al., 1991). The first experiment tested older versus younger observers in their capacity to retain spatial information while in the presence of a mask stimulus during retention.

# 2.1. Methods

#### 2.1.1. Subjects

Twenty subjects participated in this study. The experimental group consisted of 4 men and 6 women aged 65 to 80 years old (mean age of  $69.9 \pm 5.45$ ). The control group consisted of 5 men and 5 women aged 22-34 years old (mean age of  $28.2 \pm 4.61$ ). All subjects from the experimental group and six subjects from the control group were trained psychophysical observers. Everyone was tested after having determined their ocular health with a complete visual examination (refraction (best corrected visual acuity for near and far), ophthalmoscopy, biomicroscopy, tonometry, stereoscopy, central and peripheral field of vision). 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 (8 had 6/6 and 2 had 6/7.5) and 6/6 or better for the young observers. All subjects had good ocular and general health based on their medical history. The education level of our older population was relatively high for this age group. All except one (completed primary school) had completed their high school and three had university degrees.

# 2.1.2. General procedure (apparatus and stimuli)

A Macintosh IIci computer interfaced with a standard 13" Macintosh RGB calibrated monitor was used to present stimuli and collect data. The monitor was the only source of light and the mean luminance of the background was 60 cd/m<sup>2</sup>. The same general calibration procedures were used as described in Faubert (1991).



Fig. 1. Scheme of the stimuli presentation for Experiment 1 (presented one after the other). The task was to report whether the second stimulus was oriented to the right or to the left, and to determine in which of two intervals, T1 or T2, the higher spatial frequency stimulus was presented.

The stimuli consisted of a vertical Gabor spatial frequency grating with a standard deviation of 1.32 (see Fig. 1 for an example of the stimuli used) presented within a truncated 1 s temporal envelope with a standard deviation of 0.25 s. That is, the temporal Gaussian window had a plus and minus 2 standard deviation range. This means that the initial contrast onset and offset were abrupt but only for 2.5% of the tested contrast value each time. The stimulus smoothly increased and decreased for 95% of the tested contrast for a given trial with a 0.25 s standard deviation. This has no incidence on the sensitivity values but reduces the presentation time for 0.5 s for each trial. We used the same temporal Gaussian window for the mask stimuli.

Viewing distance was 3 m (to minimize any effect of loss of accommodation in the older group) and testing was binocular. To compensate for the possible loss of accommodation of the aging lens, a 0.30 diopter lens was used for the older observers. A brief demonstration and practice session (eight trials) were always conducted prior to testing in order to familiarize the subjects with the task. A single tone (100 ms duration with frequency of 830 Hz) would signal the first interval and a double tone (100 ms for each tone separated by 100 ms pause) of the same frequency would signal the second interval. All observers reported having no difficulty hearing and distinguishing the tones. Once both intervals had been presented, no time restriction was imposed for the subject's response. Subjects pressed a key to respond. After the subject's response, a two second pause preceded the next trial.

#### 2.1.3. Procedure: working memory and mask task

DT were established using a two-alternative temporal forced choice staircase with eight reversals (as described in the contrast procedure below). Steps of varying Weber fractions were used (usually 0.1, 0.05, 0.025, 0.01). All stimuli (test and masks) were presented at 0.5 log units of luminance contrast above threshold for each observer, based on the initial individual values obtained. A 5 cpd reference stimulus was presented for 1 s, followed by an ISI and a comparison stimulus of 5 cpd +  $\Delta F$  (delta frequency) for 1 s. The presentation of the reference and comparison stimulus was in random order. The

frequency, phase, and contrast of the reference stimulus was varied by  $\pm 10\%$  to prevent subjects from making a long term representation of the stimulus (Magnussen et al., 1991). The subject had to press 1 or 2 whether the stimulus of the highest spatial frequency (finest bars) was presented in the first or second interval (2IFC).

A "memory mask", was added halfway into the ISI. The "memory mask" consisted of a Gabor of either 1.25 or 5 cpd. Preliminary data on three older and three younger subjects suggested no main effect of the ISI length for the present conditions (see also Sara & Faubert, 2000) so an ISI of 3 s was used in this experiment. The memory masker stimulus was oriented 5° clockwise or counterclockwise from vertical (Fig. 1). The mask was presented in the middle of the ISI (temporal Gaussian peaking at 1.5 s of the ISI). Subjects had to verbally report the orientation of the memory mask while performing the discrimination task. The observers had no difficulty performing this task and were generally 100% correct at making the orientation judgments. It was previously demonstrated that orientation of the mask frequencies did not change the masking effect on the memory task (Magnussen et al., 1991). By designing this task we could determine the effect of the memory masker while being certain that the observers actually processed the mask stimulus. All the conditions were tested for each subject.

#### 2.1.4. Procedure: contrast thresholds

Before performing the WM and mask tasks we first determined individual contrast thresholds. This was done so that we could present the stimuli at an equivalent supra-threshold contrast level for each observer and for each spatial frequency condition (including masks). This was to minimize individual differences in sensory input during the WM experiment. Contrast detection thresholds were determined using a two-alternative temporal forced choice staircase with eight reversals. Contrast was initially set above threshold, based on values determined with a modified ascending adjustment method. The average of the last six reversals was taken as the threshold value. Four trials were performed at a contrast level, which constituted one step in the staircase. If no mistake was made in one block (100% correct), then a new block with a lower contrast was presented. If one mistake occurred (75% correct), a block using the same value was presented and this block counted as an inversion. If two mistakes (or more) were made (50% correct or less), a new block with a higher value was presented. Contrast changed by 0.175, 0.125, 0.0875, 0.0625 or 0.05 log units respectively. Thresholds were calculated as the mean of the last six values where the staircase reversed. Usually, threshold could be established within 40 trials. Staircases for different spatial frequencies were embedded in the same session. The

subject's task was to press one or two whether the stimulus appeared in the first or second interval.

The complete experiment (contrast and WM tasks) lasted about 90 min. Subjects typically completed all conditions in one (with breaks) or two sessions.

# 2.2. Results

Group DT expressed in Weber fractions are plotted in Fig. 2 as a function of masking conditions. A 2 × 3 splitplot ANOVA (age (between variable) × mask (within variable)) revealed no statistically significant difference for either group (F(1, 18) = 2.371, p = 0.141) or masking condition (F(1, 18) = 1.020, p = 0.371). Furthermore, the results of this experiment illustrate that the effect of masking is very weak, if present, even in the young observers.

#### 2.3. Discussion

We found that the addition of a memory mask during the retention interval did not significantly affect retention capacity. This is different from what would be predicted from Magnussen's model. In our task, subjects had to report the orientation of the mask ensuring that the stimulus was encoded. Magnussen and colleagues demonstrated that mask orientation did not have an effect on performance so our differences should not be attributed to orientation. Therefore, either the mask orientation does have an effect on masking or the masking effects observed in these types of stimuli are not very robust. The later explanation would argue against a low-level encoding model for VWM of spatial information. Other researchers have also failed to report masking effects on VWM experiments. For instance Thompson, Stone, and Walton (1996) reported failure to replicate masking effects with velocity judgments for motion stimuli unlike what was reported by Magnussen and colleagues (Magnussen & Greenlee, 1992).



Fig. 2. Mean DT expressed in Weber fractions obtained in Experiment 1 for the young and older group as a function of a 5 cpd mask, a 1.25 cpd mask, and the no mask condition, for an ISI of 3 s. The results for the older subjects are grouped to the left side of the figure and the results for the younger subjects are grouped to the right side of the figure. Error bars indicated standard errors of the mean for each group.

In essence, our present results support previous studies on aging and VWM for simple visual attributes that report no loss of information for vernier acuity (Fahle & Daum, 1997), spatial interval (Latham & Barrett, 1998), luminance defined squares (Sara & Faubert, 2000) and luminance defined spatial frequency information (McIntosh et al., 1999). We did not find an effect of age on VWM when a mask was used during the retention task.

# 3. Experiment 2: Intra- and inter-attribute spatial frequency discrimination in aging

To extend the previous experiment, we assessed whether aging had an effect on the capacity to retain spatial information between different attributes. Assuming that these attributes are initially processed separately and then compared at a higher level (Cavanagh, 1988) we may expect a larger deficit from aging under these conditions due to limited resources.

### 3.1. Methods

# 3.1.1. Subjects

Twenty subjects participated in this study. The experimental group consisted of 5 men and 5 women volunteers between 62 and 80 years of age (mean age of  $70.4 \pm 4.99$ ). The control group consisted of 4 men and 6 women between 24 and 33 years of age (mean age of  $29.6 \pm 2.80$ ). Five subjects from the experimental group and four from the control group had previously participated in studies in our laboratory but all were naive to this task. Everyone was tested after having determined their ocular health with a complete visual examination (refraction (best corrected visual acuity for near and far), ophthalmoscopy, biomicroscopy, tonometry, stereoscopy, central and peripheral field of vision). 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 (7 had 6/6 and 3 had 6/7.5) and 6/6 or better for the young observers. All subjects had good ocular and general health based on their medical history. The education level of our older population was relatively high for this age group. All had completed their high school and three had university degrees. Color vision was also normal as assessed by the Hardy-Rand-Rittler (HRR) pseudoisochromatic plates.

# 3.1.2. General procedure (apparatus and stimuli)

The same setup as in Experiment 1 was used. The monitor was the only source of light and the mean luminance of the background was  $18.5 \text{ cd/m}^2$ . Three colors were used: red, green and yellow. The first two, red and green, represent the guns of the monitor with CIE

u'v' coordinates of 0.44 and 0.53 for red, 0.12 and 0.56 for green. The third color, yellow, is a mixture between the red and green guns with CIE u'v' coordinates of 0.20 and 0.55. The spectroradiometric composition of the red and green guns have been previously described in Faubert (1994). Luminance (yellow) or color (red/green) defined gratings were presented on a yellow background. The color-defined gratings consisted of red/green isoluminant gratings. Isoluminance was measured for each observer using heterochromatic flicker photometry. Briefly, two flickering gratings (one red and one green) were superimposed at a rate of 15 Hz. The luminance of the red grating remained fixed (at 100% contrast) and the observer adjusted the luminance of the green grating until the impression of flicker was minimized. This value was then used for the equiluminance condition. The luminance defined grating consisted of a yellow/darkyellow grating adjusted for the equiluminance values at a cone-contrast of about 15%. The contrast used for the luminance grating corresponded to an equivalent cone excitation to that of the isoluminant gratings. The same method has been used in a previous study (Bilodeau & Faubert, 1999).

Other than the color or luminance-defining attribute, the stimuli had the same general appearance. They consisted of 1.25 cpd Gabor gratings with a standard deviation of 1.7° presented in a 1 s temporal envelope with a standard deviation of 0.3 s. Observers were seated 57 cm away from the monitor with their head and chin supported by a rest. Testing was binocular. To compensate for the loss of accommodation of the aging lens, a 1.75 diopter correction was added for the older observers. A brief demonstration and practice session (eight trials) were always carried out prior to testing, in order to familiarize subjects with the task. A single tone (100 ms duration with frequency of 830 Hz) would signal the first interval and a double tone (100 ms for each tone separated by 100 ms pause) of the same frequency would signal the second interval. All observers reported having no difficulty hearing and distinguishing the tones. Once both intervals had been presented, no time restriction was imposed on the subject's response. Subjects pressed a key to respond. After the subject's response, a two second pause preceded the next trial.

# 3.1.3. Procedure

The same staircase procedure and controls were used as in Experiment 1 (work memory task). A 1.25 cpd reference stimulus was presented for 1 s, followed by an ISI of either 1 or 10 s and a comparison stimulus of 1.25 cpd +  $\Delta F$  of 1 s. The presentation of the reference and comparison stimulus was in random order. One ISI and one attribute condition was tested at a time. The memory task was the same as in Experiment 1.

In order to examine the influence of attribute definition on VWM, three conditions were tested. In the first condition, the reference and comparison stimuli were both defined by luminance (LL condition), whereas in the second condition, the reference and comparison stimuli were both defined by color (CC condition). In the third condition, (Inter-attribute condition), the reference and comparison stimuli were respectively defined by a different attribute (color-luminance or luminancecolor). All conditions were repeated three times. The order of the replications was randomized and the two sub-conditions were also randomized within the interattribute block conditions. The complete experiment lasted about 5 h. Subjects typically completed all conditions in two or three sessions.

### 3.2. Results

For each individual, the DT from the three trials were averaged. Group DT expressed in Weber fractions for the three conditions, LL, CC, and Inter are plotted as a function of ISI. Fig. 3(a) shows the data obtained for the luminance and color intra-attribute conditions and Fig. 3(b) illustrates the results for the inter-attribute conditions. We can see in Fig. 3(a) that the LL and CC conditions produced similar thresholds whereas the inter-attribute condition (3b) produced higher thresholds. This is true even for the younger observers as demonstrated in Fig. 3(c) where we used a different scale to emphasize the difference between conditions in the young observer group. As can be seen from the graphs, the older observers consistently performed worse than the younger ones. This effect is stronger in the inter-attribute condition (3b). There seems to be a tendency for thresholds to increase with time especially for the younger subjects. This tendency was also reported by Regan (1985) but, as in this study, failed to reach statistical significance. A  $2 \times 2 \times 3$  splitplot ANOVA (age (between)  $\times$  ISI (within)  $\times$  attribute condition (within)) revealed a main effect of age (F(1, 18) = 13.34, p = 0.002), and a main effect of attribute conditions (F(2, 18) = 8.53, p = 0.001). Neither a main effect of ISI (F(1, 18) = 1.51, p = 0.24) nor significant interactions between age, attribute conditions, and ISI were found (F < 1). The thresholds obtained by the older observers were, on average, about twice as high for the inter-attribute condition and about 1.5 times higher for the single attribute conditions than the ones of the younger subjects.

# 4. General discussion

The results of this experiment indicate that there is no loss of spatial frequency information with a delay of 10 s, regardless of the defining attribute. Thresholds obtained when the stimuli were defined only by color, CC condition, were very similar to the ones obtained with luminance defined stimuli (LL) as shown in Fig. 3. This suggests that color is as efficient as luminance for encoding, storage, and retrieval of visual spatial frequency information for our conditions. This is interesting for two reasons. First, some visual information, such as contrast, has been shown to decay faster than spatial frequency or velocity information (Magnussen et al., 1996). Secondly, Gregory (1977) had suggested that luminance was the most efficient defining attribute, therefore the DT should be lower for luminance gratings. In this study, we compared color with luminance for equivalent cone contrast conditions and found no difference between the DT for spatial frequency information defined by a single attribute. One possible explanation for the equivalent efficiency in defining spatial frequency information and retention is that color and luminance attributes are the most basic attributes and require the lowest level of processing. It is also possible that, because we have equated for cone contrast, we compensated for the relative input strength of both the luminance and color signal. This would imply that the differences reported previously may be attributable to unequal input strength in the stimuli used in those studies.

In addition to measuring thresholds when stimuli to be compared were defined by the same attribute, LL and CC conditions, we also measured them when the stimuli



Fig. 3. Mean DT expressed in Weber fractions obtained in the luminance  $(\Box)$ , color  $(\bigcirc)$ , (shown in 3(a)), and Inter-attribute ( $\blacktriangle$ ) conditions (shown in 3(b)) as a function of ISI. Error bars indicate standard error of the means for each condition. The results of the younger group are represented by open symbols while the older group data are illustrated as closed symbols. In panel b the error bars for the young observers are not apparent because they are obscured by the symbols. The young group data are redrawn in 3c on a different scale to emphasize the differences between the intra- and inter-attribute conditions.

were defined by two different attributes, inter-attribute condition. Thresholds in the inter-attribute condition were significantly higher than in the LL and CC conditions, however, the thresholds remained relatively stable between one and 10 s intervals. In this task, the first stimulus, defined by luminance or color, is stored, the second stimulus is then compared to the stored representation of the first stimulus. Comparisons were performed equally well for delays of both one and 10 s, suggesting that the stored representations did not decay. The elevation in thresholds obtained in the interattribute condition, relative to the LL and CC conditions, suggests that the comparison between reference and test stimuli is more complex and requires more processing resources because the two mechanisms responsible for processing luminance and color information are used to perform this task.

Lages and Treisman (1998) have suggested that a decision criterion can be maintained in WM rather than the spatial frequency information. These authors compared DT for spatial frequency gratings in the presence of the reference stimuli, to thresholds obtained without the presentation of the reference stimuli. They found similar DT, supporting their hypothesis that discrimination over a period of time results from the operation of a criterion-setting process rather than a long-term sensory retention. Their argument, however, cannot account for our results in this particular study. If a criterion-setting process is what operates on thresholds, then similar thresholds should have been obtained when our test and reference stimuli were defined by a different attribute. Our thresholds were significantly higher in this condition, indicating that, at least, in this context, some form of sensory representation was stored.

Our results also have implications in regards to how inter-attribute information is processed at different levels. Rivest and colleagues have found that information defined by different attributes can be used equally well for border formation (Rivest & Cavanagh, 1996) or for orientation discrimination (Rivest et al., 1997). It appears that for both border information and orientation discrimination, the inter-attribute information is compared at a common site but at what level? Our results show that when the spatial characteristics themselves are defined by different attributes, the information is not used at a common site, suggesting that these lower level mechanisms are initially processed in parallel but are later compared at a common site. Similar results have been found in studies with the motion induction illusion (Faubert & von Grünau, 1995; Von Grünau & Faubert, 1994). It was demonstrated that a single primer defined by an attribute could induce the motion illusion in a bar defined by another attribute. The motion illusion was easily perceived across different attributes indicating that the information necessary to generate this illusion was easily transferred between attributes and processed at a common site (Von Grünau & Faubert, 1994). However, when more than a single primer was used (split-priming experiments), the attribute characteristics of the primers and the bar were crucial for generating the motion illusion (Faubert & von Grünau, 1995). In their series of experiments, Faubert and von Grünau further demonstrated that the single priming condition was probably generated by higher-level attention processes while in the split-priming condition, there were lower-level factors influencing the illusion such as attribute characteristics, eye of origin (dichoptic experiments) and spatial configurations. Therefore, the motion induction studies demonstrate that when lower-level mechanisms are involved, attribute characteristics influence the results implying that the attributes are initially processed in different locations. When higher-level factors are involved, information from different attributes are compared at a common site. Similarly, the results of our present study imply that for a low-level comparison, such as spatial frequency discrimination, the attributes are operating at different sites. In contrast, when higher-level tasks such as border formation are evaluated, the information from the different attributes are subsequently compared at a common site (Rivest & Cavanagh, 1996).

To examine the effect of age on VWM for spatial frequency information defined by single or different attributes; we compared the performance of older subjects with that of younger subjects for each of the attribute pairs. We found that older subjects performed equally well as younger subjects for the retention of spatial frequency gratings regardless of the defining attribute. In other words, there was no decay of spatial information in VWM in aging. This result is supported by previous findings (McIntosh et al., 1999; Sara & Faubert, 2000). The performance with color defined stimuli was similar to the one obtained with luminance defined stimuli. We equated the sensory input for each individual by using their equiluminance value. Older subjects typically required higher green to red contrast ratios. Nonetheless, our results indicate that, when sensory input is controlled, the color pathway is not selectively compromised in aging. Nguyen-Tri, Overbury, and Faubert (1999) have also reported an intact color pathway in aging with chromatic motion sensitivity experiments. As in this study, there were substantial differences between young and older observers for equiluminance values, there were no significant differences in motion thresholds between age groups when the individual differences in equiluminance were accounted for. In the present study, older subjects consistently obtained higher thresholds than younger subjects for spatial frequency discriminations. This result, which was also obtained in our previous study, (Sara & Faubert, 2000) points to a perceptual deficit in aging rather than a WM deficit for spatial information.

In agreement with results obtained from the younger observers we found that thresholds increased in the inter-attribute condition for the older observers. However, there was a greater effect of threshold elevation in the older group for the inter-attribute condition. The thresholds in the inter-attribute condition were approximately twice the ones obtained with the younger group, whereas they were about 1.5 higher than the ones for the younger group in the single attribute conditions (CC and LL). Other studies have also reported this type of perceptual deficit in aging. Habak and Faubert (2000) found that thresholds for the perception of second order (complex) stimuli were more elevated for older relative to young observers as compared to the results for the first order (simple) stimuli. The finding that the older observers were more affected in the inter-attribute condition may be explained by the reduction of processing resources hypothesis. As discussed earlier, this task was more complex, and thus, increased processing demands. Since older subjects have presumably fewer processing resources available than younger subjects do, it follows that their performance should be significantly worse than in the single attribute conditions.

The spatial frequency DT in the second experiment for the LL condition were lower than the ones obtained in the no-mask condition of Experiment 1. This can be explained by the simple fact that we used a preset cone contrast level of 15% in the second experiment while the contrast values used in the first experiment were set at 0.5 log units above individual thresholds. Therefore, we cannot conclude that the lack of masking effects in the first experiment are due to some form of interference caused by the mask conditions.

Recently, a series of functional imaging studies have been conducted examining the cortical activation of young and older observers for spatial memory tasks similar to Experiment 1 of the present study (Della-Maggiore et al., 2000; Bennett, Sekuler, McIntosh, & Della-Maggiore, 2001; McIntosh et al., 1999). They found no effect of aging on the psychophysical performance for retaining spatial frequency information much like our own results. What is interesting in those studies is that they found that the neural substrates involved in performing these tasks were different between older and younger observers even if behavioral performance was identical for both groups. They suggested that this reorganization of the older brain, may be the consequence of a larger recruitment of neural networks required to perform a given task, which has become necessary to compensate for weakened areas. We are in agreement with this conclusion. This proposition is in accordance with the processing resources hypothesis of aging and may shed light as to why older observers do not show decrements for some low-level memory tasks. It is conceivable that the alternate neural circuits available are limited and that simple memory tasks may not saturate

these alternatives. However, if a task is made more complex, the compensatory 'neural routes' required to perform this task in the aging brain should increase in a non-linear fashion where a level of saturation can rapidly be reached. The study by Habak and Faubert (2000) was based on this rationale. We argued that processing of a second order stimulus should be more affected by aging than a first order stimulus. The argument was based on the fact that processing second order stimuli requires larger neural networks and the consequences of aging (weakened neural network) would be more obvious under these conditions. Our results supported this hypothesis and are congruent with the functional imaging studies sited above.

The functional imaging studies may also shed light on the Sara and Faubert (2000) study. We demonstrated, with a somewhat different paradigm, that WM for information on size was also unaffected by aging when compensating for individual differences in sensory input. However, when the same size judgment had to be made from simultaneously presented squares, a significant loss of aging was observed even if there were no age effects when the same judgments were made sequentially. It is important to note that the task itself was exactly the same, i.e. the subject had to compare the size difference between two squares. This led us to speculate that, if the neural networks required to process the size of two squares had to be accessed simultaneously, any weakness of the circuit would become more obvious. Alternatively, if the compensating neural circuits can be accessed in alternation (first square stored then compared with the second) the evidence of a weakened neural circuit may be less obvious, even if the sum of the sequentially accessed circuits may involve a larger total network than when the two squares have to be accessed simultaneously. This hypothesis, which we will call the 'simultaneous access deficit' hypothesis remains speculative and requires much further testing.

#### 5. General conclusions

In summary, our findings indicate that, color, luminance and inter-attribute information for simple stimuli are well maintained in VWM and VWM performance for simple stimuli is not affected by aging as evidenced by the lack of ISI effects in Experiment 2. The data also illustrate that visual masking during retention has no consistent effects on retention for young or older observers. Stimuli defined by different attributes increased the DT for both one and 10 s ISIs, suggesting that this task requires more processing resources than do singleattribute conditions. This also suggests that, although the initial processing for spatial frequency information appears equally efficient for luminance and color, they are not processed at a common site. Once the information is processed by each attribute mechanism, they can then be compared at a common site as evidenced by previous border judgment and the motion induction experiments. Furthermore, older observers were more affected in the inter-attribute condition supporting the reduction of processing resources hypothesis of aging. Although the psychophysical response for a VWM task with simple stimuli may not be affected, it is not to say that there is no underlying change in the neural networks required to process such information in the older individuals. The functional imaging studies clearly demonstrate that changes have occurred in the neural circuitry involved but they may not have reached a point of saturation when simple stimuli have to be processed. When larger networks have to be accessed, either by way of simultaneous processing or when the stimuli are more complex, the underlying dysfunction may become more obvious and could be expressed by functional deficits.

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