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Scene perception in age-related macular degeneration: Effect of spatial frequencies and contrast in residual vision

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ABSTRACT

Age-related macular degeneration (AMD) is characterized by a central vision loss. Here, we investigated the ability of AMD patients to process the spatial frequency content of scenes in their residual vision, depending of the luminance contrast level. AMD patients and normally-sighted elderly participants (controls) performed a categorization task involving large scenes (outdoors vs. indoors) filtered in low spatial frequencies (LSF), high spatial frequencies (HSF), and non-filtered scenes (NF). Luminance contrast of scenes was equalized between stimuli using a root-mean square (RMS) contrast normalization. In Experiment 1, we applied an RMS contrast of 0.1 (for luminance values between 0 and 1), a value situated between the mean contrast of LSF and HSF scenes in natural conditions. In Experiment 2, we applied an RMS contrast of 0.3, corresponding to the mean contrast of HSF scenes in natural conditions. In Experiment 3, we manipulated four levels of linearly-increasing RMS contrasts (0.05, 0.10, 0.15, and 0.20) for HSF scenes only. Compared to controls, AMD patients gave more non-responses in the categorization of HSF than NF or LSF scenes, irrespective of the contrast level of scenes. Performances improved as contrast increased in HSF scenes. Controls were not differentially affected by the spatial frequency content of scenes. Overall, results suggest that LSF processing is well preserved in AMD patients and allows efficient scene categorization in their parafoveal residual vision. The HSF processing deficit could be partially restored by enhancing luminance contrast.

1. Introduction

Age-related macular degeneration (AMD) is characterized by central vision loss caused by the destruction of macular photoreceptors. AMD therefore affects low-level visual functions of central vision, such as acuity, high spatial resolution and contrast sensitivity, and consequently, the activities of daily life, such as reading (Fine & Peli, 1995; Fletcher, Schuchard, & Watson, 1999; Legge, Rubin, Pelli, & Schleske, 1985), face recognition (Bullimore, Bailey, & Wacker, 1991; Tejeria, Harper, Artes, & Dickinson, 2002) and processing of facial emotion (Boucart, Dinon, et al., 2008). Interestingly, activities which involve the peripheral residual vision of AMD patients, such as objet and scene perception (Boucart, Despretz, Hladiuk, & Desmettre, 2008; Boucart, Moroni, Despretz, Pasquier, & Fabre-Thorpe, 2010), driving (Rovner & Casten, 2002), and mobility (Hassan, Lovie-Kitchin, & Woods, 2002; Salive et al., 1994) are also affected.

Many studies have directly demonstrated that in AMD patients contrast sensitivity decreases for middle and high spatial frequencies in sinusoidal gratings (Brown & Lovie-Kitchin, 1988; Kleiner, Enger, Alexander, & Fine, 1988; Midena, Degli Angeli, Blarzino, Valenti, & Segato, 1997). Recent studies have focused on the residual abilities of AMD patients to process more complex daily visual stimuli, such as objects, faces, and scenes. Tran, Guyader, Guerin, Despretz, and Boucart (2011) showed that the detection of an animal in a scene is impaired in AMD patients, but that this could be improved by surrounding the animal with a white space. AMD patients were also more affected by contrast reduction during a similar animal detection task than normally-sighted, age-matched people (Tran, Despretz, & Boucart, 2012). In Bordier, Petra, Dauxerre, Vital-Durand, and Knoblauch (2011), AMD patients had to name an object in a scene sequence starting with a scene in low spatial frequencies and spatial frequency information was progressively added. Results showed a reduction in the

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bandwidth necessary for the object identification when the background was darkened by lowering its luminance. Other findings have pointed to a deficit for AMD patient in the processing of high spatial frequencies in complex visual stimuli. When assessing the recognition of facial emotional expressions in AMD patients, Boucart, Dinon, et al. (2008) showed that visual processing was impaired when the decision relied on the perception of fine details conveyed by high spatial frequencies. Using a categorization task involving large scenes which encompassed the parafoveal vision, Musel et al. (2011) demonstrated a specific deficit in AMD patients in the processing of high spatial frequencies (HSF) in scenes, and preserved skills in the processing of low spatial frequencies (LSF). The specific visual impairment for HSF scene categorization is consistent with the loss of photoreceptors and ganglion cells specifically tuned to HSF in the central area of the macula in AMD patients. However, luminance contrast is higher for LSF than for HSF scenes. Luminance contrast in scenes decreases as spatial frequency increases, following a 1/f function (Field, 1987). The low luminance contrast in HSF scenes may have contributed to the HSF deficit.

The aim of the present study was to examine the processing of spatial frequencies in AMD patients' parafoveal residual vision, and in particular to investigate whether low luminance contrast in scene could in fact explain the visual deficit of AMD patients in the categorization of HSF scenes. For this purpose, we conducted three experiments in which AMD patients and normally-sighted elderly participants had to categorize indoor and outdoor scenes filtered in LSF and HSF, and non-filtered scenes (NF). From a pragmatic point of view, this categorization task can be performed whatever type of filter is used (low-pass, high-pass, or pass-band). Furthermore, this task is simple and quick to administer, but also easy to perform even for patients with age-related macular degeneration (Musel et al., 2011). We examined the effect of contrast equalization on spatial frequency processing in the residual vision of AMD patients in the two first experiments. In the third experiment, we directly examined whether contrast increase could improve the processing of HSF information.

2. Experiment 1

Experiment 1 aimed specifically to investigate whether the deficit of AMD patients for categorizing HSF scenes (Musel et al., 2011) could be explained by the low luminance contrast in HSF scenes. In this experiment, luminance contrast of NF, LSF, and HSF scenes was equalized using an RMS (root mean square) contrast normalization. RMS contrast corresponds to the standard deviation of luminance values. It is the most frequently-used normalization, and it has been shown to be the most reliable indicator of the visibility of broadband filtered images (Bex & Makous, 2002). We chose an RMS value situated between the mean contrast values of LSF and HSF scenes in natural conditions (RMS contrast of 0.1 for luminance values between 0 and 1) in order to avoid affecting one spatial frequency condition more than another. Therefore, this contrast normalization enhances contrast in HSF scenes while reducing contrast in LSF scenes. If the visual deficit of AMD patients in scene categorization is mainly explained by the spatial frequency content, we expected that AMD patients would commit more errors than controls for HSF only, irrespective of the luminance contrast level.

2.1. Materials and methods

2.1.1. Participants

Nineteen patients with exudative AMD (Table 1) were included in the experiment. They were followed and treated with intravitral injections of ranibizumab using a pro re nata regimen in the course of a flexible anti-VEGF therapy regimen for the treatment of neovascular AMD. Patients were seen monthly and treated on an "as-needed" basis. The inclusion criterion was visual acuity between 1 and 0.2 LogMAR in the most severely impaired eye. Only one eye was tested in twelve patients (seven males; mean age ± S.D. = 69 ± 6 years; range 60–77; AMD 1–12 in Table 1). Patients with unilateral AMD were tested on their pathological eye. Patients with bilateral AMD were tested on the eye with the best-corrected visual acuity. Twelve normally sighted elderly participants (six males; 65 ± 3 years; range 61–72; Table 1) were also tested unilaterally, in the eye with the best-corrected visual acuity (Control group). The inclusion criterion for controls was visual acuity between 0.2 and 0 LogMAR in the selected eye. Seven patients with unilateral AMD (five males; 73 ± 8 years; range 62–82; AMD 13–19 in Table 1) were tested twice, once on the AMD eye and a second time on the healthy eye. Performances measured in the healthy eye allowed us to use patients as their own controls. The order of the eye tested was counterbalanced across patients.

Table 1
Demographic and clinical data of Experiment 1. Patients AMD 1 to AMD 12, and Controls were tested in only one eye. Patients AMD 13 to AMD 19 all have unilateral AMD. They were tested in both eyes (AMD eye and healthy eye).

	Gender	Age (years)	Lesion type	Eye test	Visual acuity (LogMAR)		Gender	Age (years)	Visual acuity (LogMAR)
AMD 1	M	72	Bilateral	Left	0.2	Control 1	M	61	0
AMD 2	M	72	Bilateral	Right	0.2	Control 2	M	62	0
AMD 3	F	77	Bilateral	Left	0.2	Control 3	F	63	0
AMD 4	M	61	Bilateral	Left	0.3	Control 4	F	63	0
AMD 5	M	70	Unilateral	Right	0.3	Control 5	M	66	0
AMD 6	F	74	Unilateral	Left	0.3	Control 6	F	67	0
AMD 7	M	76	Bilateral	Left	0.4	Control 7	M	67	0
AMD 8	M	63	Unilateral	Right	0.6	Control 8	F	68	0
AMD 9	M	60	Unilateral	Right	0.7	Control 9	F	68	0
AMD 10	F	67	Bilateral	Left	0.7	Control 10	M	65	0.1
AMD 11	F	73	Bilateral	Left	0.8	Control 11	F	72	0.1
AMD 12	F	70	Bilateral	Left	0.9	Control 12	M	61	0.2

	Gender	Age (years)	Lesion type	AMD eye	Visual acuity (LogMAR) AMD eye	Visual acuity (LogMAR) Healthy eye
AMD 13	M	82	Unilateral	Right	0.2	0
AMD 14	F	67	Unilateral	Left	0.3	0
AMD 15	M	80	Unilateral	Right	0.6	0.1
AMD 16	M	62	Unilateral	Right	0.7	0
AMD 17	M	77	Unilateral	Right	0.7	0.1
AMD 18	F	80	Unilateral	Right	0.7	0.1
AMD 19	M	65	Unilateral	Left	1	0

Participants with psychiatric, neurological, and ocular (glaucoma and multiple sclerosis) disorders were not included in the study. All participants gave their informed written consent before participating in the study, which was carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans, and approved by the local ethics committee (Comité de protection des personnes Sud-Est V, ID RCB: 2011-A01551-40).

2.1.2. Stimuli and procedure

Stimuli were 20 photographs of scenes (1042 × 768 pixels, 256-level gray-scales) classified into two categories (10 outdoor scenes and 10 indoor scenes; see Fig. 1) with a visual angle of 24 × 18 degrees, in order to stimulate both the central and the peripheral visual field (Musel et al., 2013). Exemplars from the two categories have similar amplitude spectra and both categories were equivalent in terms of visual cluttering (for further details, see Kauffmann, Ramanoel, Guyader, Chauvin, & Peyrin, 2015; Ramanoel, Kauffmann, Cousin, Dojat, & Peyrin, 2015). For each scene, a LSF and a HSF stimulus were created. Filtered images were created using the MATLAB image processing toolbox (Mathworks, Inc., Sherborn, MA, USA). The spatial frequency content of scenes was filtered by multiplying the Fourier transformation of original images by Gaussian filters. The standard deviation of the Gaussian filter is a function of the spatial frequency cut-off, for a standard attenuation of 3 dB. For HSF stimuli, we removed spatial frequency information below 6 cpd (i.e. high-pass cut-offs of 144 cycles per image). For LSF stimuli, we removed frequency content above 1 cycle per degree (cpd; i.e. low-pass cut-offs of 24 cycles per image). These values are similar to the ones used in previous study on spatial frequency processing during scene perception (Kauffmann et al., 2015; Ramanoel et al., 2015). The spatial frequency content of scenes was not modified for non-filtered (NF) stimuli. Images were then normalized to obtain a mean luminance of 0.5 for luminance values of between 0 and 1 (mean luminance of 128 on a gray-level scale). In the LUM condition, the contrast of filtered scenes was not modified. In the RMS condition, scenes were normalized to obtain an RMS contrast of 0.1 (25.6 on a gray-level scale; value situated between the mean contrast value of HSF and LSF scenes in natural conditions: 0.03 and 0.23, respectively in the LUM condition). This resulted in 6 versions of each scene.

Stimuli were displayed using E-Prime software (E-Prime Psychology Software Tools Inc., Pittsburg, PA) on a 17' monitor, with a resolution of 1024 × 768 pixels, and a viewing distance of 55 cm. To maintain the distance and central position, the participant's head was supported by a chinrest. The experiment consisted of 120 trials. In half of the trials the scene was indoor, and in the other half the scene was outdoor. This resulted in 10 trials for each of the 12 experimental conditions: LUM-NF-indoor, LUM-NF-outdoor, LUM-LSF-indoor, LUM-LSF-outdoor, LUM-HSF-indoor, LUM-HSF-outdoor, RMS0.1-NF-indoor, RMS0.1-NF-outdoor, RMS0.1-LSF-indoor, RMS0.1-LSF-outdoor, RMS0.1-HSF-indoor, and RMS0.1-HSF-outdoor. Each trial began with a central fixation point for 500 ms accompanied by a sound, immediately followed by a filtered scene for 300 ms. The quality of the central fixation was controlled by the experimenter. NF, LSF, and HSF outdoor and indoor scenes were displayed randomly during the experiment and the order of scenes was randomized across participants.

Participants were asked to make a choice of category and to decide whether the scene took place indoors or outdoors. Before the experiment, participants were given a training session of eight practice trials using stimuli that differed from the ones used in the experiment. The training session revealed that when a motor response was required from participants (for example, when patients had to answer "indoor" or "outdoor" by pressing a corresponding response key with either two fingers of their dominant hand or one finger of each hand), more than half of the patients focused their attention on the keys and did not perform the visual task as well as when a verbal response was required. In order to use a procedure suited to all patients, all participants had to give a verbal response. Accuracy was recorded in each trial. If the participant did not give any response in the 3 s following stimulus

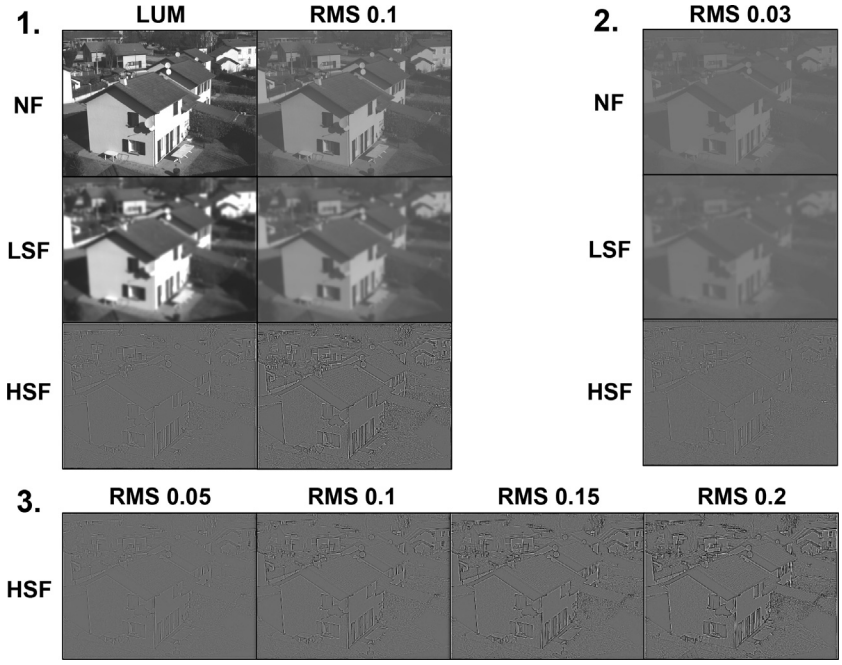

Fig. 1. Example of non-filtered (NF), low-spatial frequencies (LSF), and high-spatial frequency (HSF) outdoor scene (1) in the LUM condition and the 0.1 RMS contrast condition of Experiment 1, (2) in the 0.03 RMS contrast condition of Experiment 2, and (3) in the 0.05, 0.1, 0.15, and 0.2 RMS contrast conditions of Experiment 3. Perception of spatial frequencies may have been affected by reduction of the picture size of scenes for illustrative purposes. Image size in the figure is about 10 times smaller than the actual picture size on the screen used in the experiment, and the images presented in the figure have thus been slightly modified in order to make them more visible.

presentation, the experimenter asked the participant whether he saw the scene, and if so, whether he could provide a response. In this way, the experimenter could be ensured that the absence of a response was intentional. Otherwise, the experimenter recorded the participant's response given after his intervention despite the lack of confidence of the participant. However, participants were encouraged not to give a response if they were unable to do it, thus avoiding guessing or a bias toward any one category. Errors consisted of either a non-response or a false categorization. The experimenter then presented the next trial. The experiment lasted about 10 min.

2.2. Results

2.2.1. AMD patients vs. controls

Performances (non-response and false categorization) for AMD patients and control participants are reported in Table 2. Two $2 \times 2 \times 3 \times 2$ analyses of variance (ANOVA) for repeated measures (with Greenhouse-Geisser correction for non-sphericity) were conducted on mean non-response rate (mNR) and mean false categorization rate (mFC) with Group (AMD patients and Controls) as between-subjects factor, and Contrast (LUM and RMS0.1), Spatial frequency (NF, LSF, and HSF), and Category (indoor and outdoor) as within-subjects factors. Mean comparisons were explored using Tukey post hoc tests. The significant level of tests was set at 0.05.

The ANOVA on mNR (Fig. 2a) revealed a main effect of the Group. AMD patients responded less often than Controls (Mean ± SD: 23.2 ± 14.8% and 1.5 ± 4%, respectively; $F_{1,22} = 39.46$, $p < 0.001$). The Group × Spatial frequency interaction was significant ($F_{2,44} = 73.20$, $p < 0.001$). Mean comparisons revealed that AMD patients responded less often when categorizing HSF scenes (61.9 ± 28.6%) than NF scenes (2.1 ± 5.4%) and LSF scenes (5.6 ± 10.5%). There was no difference between NF and LSF scenes. For Controls, there was no significant differences between spatial frequencies (NF: 1.0 ± 2.9%; LSF: 0.8 ± 2.9%; HSF: 2.5 ± 6.2%). In addition, AMD patients responded less often than Controls only when categorizing HSF scenes. The Group × Spatial frequency × Contrast interaction was significant ($F_{2,44} = 28.27$, $p < 0.001$). Mean comparisons revealed a significant Spatial frequency × Contrast interaction only for AMD patients ($F_{2,44} = 61.42$, $p < 0.001$; Controls: $F_{2,44} < 1$). For the LUM condition, AMD patients responded less often when categorizing HSF scenes (85.8 ± 22.4%) than NF scenes (1.7 ± 4.6%) and LSF scenes (6.7 ± 12.6%). There was no difference between NF and LSF scenes. For the RMS0.1 condition, AMD patients responded less often when categorizing HSF scenes (37.9 ± 34.8%) than NF scenes (2.5 ± 6.2%) and LSF scenes (4.6 ± 8.4%). There was no difference between NF

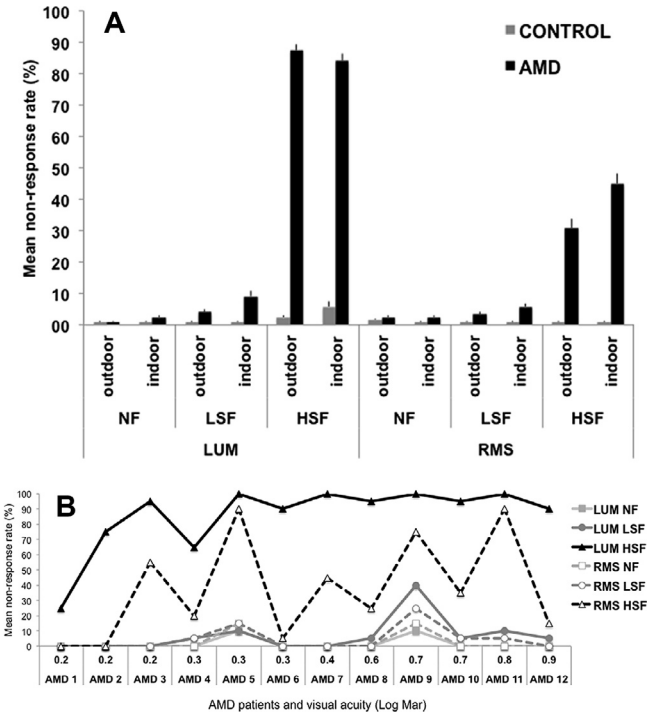

Fig. 2. (A) Mean non-response rates (%) for the categorization of non-filtered scenes (NF), low-spatial frequency scenes (LSF), and high-spatial frequency scenes (HSF) for AMD patients and normally sighted elderly participants (Control). Error bars correspond to the standard error. (B) Individual results for AMD patients.

Table 2
mNR (%) and mFC (%), and SD for categorizing NF, LSF, and HSF outdoor and indoor scenes when luminance contrast of scenes was not modified (LUM condition) and normalized with an RMS contrast 0.1 for luminance values between 0 and 1 (RMS0.1 condition) in normally sighted participants and AMD patients in Experiment 1.

		LUM					
		NF		LSF		HSF	
		Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor
Control	mNR	0.8	0.8	0.8	0.8	2.5	5.8
	SD	*2.9*	*2.9*	*2.9*	*2.9*	*4.5*	*17.3*
	mFC	0.8	0.8	0.8	0.8	0.8	3.3
	SD	*2.9*	*2.9*	*2.9*	*2.9*	*2.9*	*4.9*
AMD	mNR	0.8	2.5	4.2	9.2	87.5	84.2
	SD	*2.9*	*6.2*	*7.9*	*17.3*	*20.5*	*24.3*
	mFC	3.3	3.3	4.2	1.7	1.7	1.7
	SD	*6.5*	*4.9*	*6.7*	*3.9*	*3.9*	*3.9*
		RMS0.1					
		NF		LSF		HSF	
		Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor
Control	mNR	1.7	0.8	0.8	0.8	0.8	0.8
	SD	*2.9*	*2.9*	*2.9*	*2.9*	*2.9*	*0.0*
	mFC	0.8	0.8	0.8	0.8	0.8	0.8
	SD	*2.9*	*2.9*	*2.9*	*2.9*	*2.9*	*0.0*
AMD	mNR	2.5	2.5	3.3	5.8	30.8	45.0
	SD	*6.2*	*6.2*	*7.8*	*9.0*	*32.6*	*37.1*
	mFC	4.2	0.8	2.5	1.7	4.2	1.7
	SD	*5.1*	*2.9*	*4.5*	*3.9*	*6.7*	*3.9*

and LSF scenes. Furthermore, AMD patients gave significantly more correct responses in the RMS0.1 than in the LUM condition only for HSF scenes, suggesting an improvement of performance induced by the RMS0.1 contrast normalization for this condition.

Furthermore, the Group × Spatial frequency × Contrast × Category interaction was significant ($F_{2,44} = 8.20$, $p < 0.05$). Mean comparisons revealed that AMD patients gave significantly more correct responses for outdoors than indoors only for the HSF scenes of the RMS0.1 condition (outdoor: 30.8 ± 32.6%; indoor: 45.0 ± 37.1%). The last result suggests a more pronounced improvement induced by RMS0.1 contrast normalization for outdoor scenes.

The relationship between visual acuity and age of AMD patients and mNR for indoor and outdoor HSF scenes of the LUM and RMS0.1 conditions was statistically assessed by using Pearson correlation tests. There was no significant correlation neither between visual acuity and mNR (LUM-HSF-outdoor: $r = -0.28$, $p = 0.39$; LUM-HSF-indoor: $r = -0.22$, $p = 0.49$; RMS0.1-HSF-outdoor: $r = 0.52$, $p = 0.08$; RMS0.1-HSF-indoor: $r = 0.32$, $p = 0.32$) nor between age and mNR (LUM-HSF-outdoor: $r = 0.02$, $p = 0.95$; LUM-HSF-indoor: $r = 0.01$, $p = 0.98$; RMS0.1-HSF-outdoor: $r = -0.14$, $p = 0.68$; RMS0.1-HSF-indoor: $r = 0.05$, $p = 0.87$). Descriptive analysis on single participant data (Fig. 2b) showed that 12 out of the 12 patients have a higher NR rate for HSF than LSF and NF scenes in the LUM condition, and 10 out of the 12 patients have a higher NR rate for HSF scenes in the RMS0.1 condition.

Finally, the ANOVA on mFC did not reveal an effect of Group ($F_{1,22} = 2.48$, $p = 0.13$). Neither the Group × Spatial frequency interaction ($F_{2,44} < 1$), nor the Group × Spatial frequency × Contrast interaction ($F_{2,44} = 3.06$, $p = 0.06$) were significant.

2.2.2. AMD eye vs. healthy eye in patients

Performances (mNR and mFC) for AMD and healthy eyes are reported in Table 3. Two 2 × 2 × 3 × 2 analyses of variance (ANOVA) for repeated measures (with Greenhouse-Geisser correction for non-sphericity) were conducted on mean non-response rate (mNR) and mean false categorization rate (mFC) with Eye (AMD and healthy), Contrast (LUM and RMS0.1), Spatial frequency (NF, LSF and HSF), and Category (indoor and outdoor) as within-subjects factors. Mean comparisons were explored using Tukey post hoc tests. The significant level of tests was set at 0.05.

The ANOVA on mNR (Fig. 3a) revealed that patients responded less often using their AMD than healthy eye (Mean ± SD: 23.3 ± 12.2% and 5.8 ± 8.1%, respectively; $F_{1,22} = 27.84$). The Eye × Spatial frequency interaction was significant ($F_{2,12} = 56.18$). Mean comparisons revealed that patients tested on their AMD eye responded less often when categorizing HSF scenes (58.6 ± 22.5%) than NF scenes (2.9 ± 5.9%) and LSF scenes (5.4 ± 8.1%), while there was no difference between LSF and NF scenes. On their healthy eye, there was no difference between spatial frequencies (NF: 5.4 ± 4.8%; LSF: 1.8 ± 4.1%; HSF: 9.6 ± 15.4%). In addition, patients responded less often with their AMD than their Healthy eye only when categorizing HSF scenes.

Furthermore, the Group × Spatial frequency × Contrast interaction was significant ($F_{2,12} = 18.00$, $p < 0.01$). Mean comparisons revealed that, in the LUM condition, patients tested on their AMD eyes responded less often when categorizing HSF scenes (86.4 ± 17.1%) than NF scenes (1.4 ± 3.8%; $p < 0.001$) and LSF scenes (5.7 ± 7.7%), while there was no difference between LSF and NF scenes. On their healthy eye, there was no effect of spatial frequencies. In the RMS0.1 condition, patients tested on their AMD eye responded less often when categorizing HSF scenes (30.7 ± 28.0%) than NF scenes (4.3 ± 8.1) and LSF scenes (5.0 ± 8.5%), while there was no difference between LSF and NF scenes. On their healthy eye, there was again no effect of spatial frequencies. Interestingly, on the AMD eye, patients gave significantly more correct responses in the RMS0.1 than the LUM condition only for HSF scenes, suggesting the improvement of performance for this condition. Finally, the Group × Spatial frequency × Contrast × Category interaction was not significant ($F_{2,12} < 1$).

The relationship between visual acuity of the AMD eye and mNR for indoor and outdoor HSF scenes of the LUM and RMS0.1 conditions was statistically assessed by using Pearson correlation tests. There was no significant correlation for either experimental condition (LUM-HSF-outdoor: $r = -0.16$, $p = 0.73$; LUM-HSF-indoor: $r = -0.35$, $p = 0.44$; RMS0.1-HSF-outdoor: $r = -0.32$, $p = 0.88$; RMS0.1-HSF-indoor: $r = -0.39$, $p = 0.39$). Descriptive analysis on single participant data (Fig. 3b) showed that 7 out of

Table 3
mNR (%) and mFC (%), and SD for categorizing NF, LSF, and HSF outdoor and indoor scenes when luminance contrast of scenes was not modified (LUM condition) and normalized with an RMS contrast 0.1 for luminance values between 0 and 1 (RMS0.1 condition) in patients with unilateral AMD tested on their AMD and Healthy eyes in Experiment 1.

		LUM					
		NF		LSF		HSF	
		Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor
AMD eye	mNR	1.4	1.4	10	1.4	83.3	88.6
	SD	*3.8*	*3.8*	*11.5*	*3.8*	*20.7*	*13.5*
	mFC	4.3	4.3	2.9	2.9	1.4	5.7
	SD	*5.3*	*5.3*	*4.9*	*4.9*	*3.8*	*11.3*
Healthy eye	mNR	1.4	1.4	1.4	1.4	8.6	22.9
	SD	*3.8*	*3.8*	*3.8*	*3.8*	*15.7*	*30.4*
	mFC	1.4	1.4	2.9	4.3	2.9	11.4
	SD	*3.8*	*3.8*	*4.9*	*5.3*	*4.9*	*9.0*
		RMS0.1					
		NF		LSF		HSF	
		Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor
AMD eye	mNR	2.9	5.7	7.4	2.9	28.6	32.9
	SD	*4.9*	*11.3*	*9.5*	*7.6*	*27.3*	*28.7*
	mFC	1.4	2.9	1.4	1.4	5.7	10.0
	SD	*3.8*	*4.9*	*2.8*	*3.8*	*7.9*	*15.3*
Healthy eye	mNR	4.3	1.4	2.9	1.4	2.8	4.3
	SD	*7.9*	*3.8*	*4.9*	*3.8*	*7.6*	*7.9*
	mFC	4.9	1.4	1.4	1.4	2.9	5.7
	SD	*5.3*	*3.7*	*3.7*	*3.7*	*4.8*	*5.3*

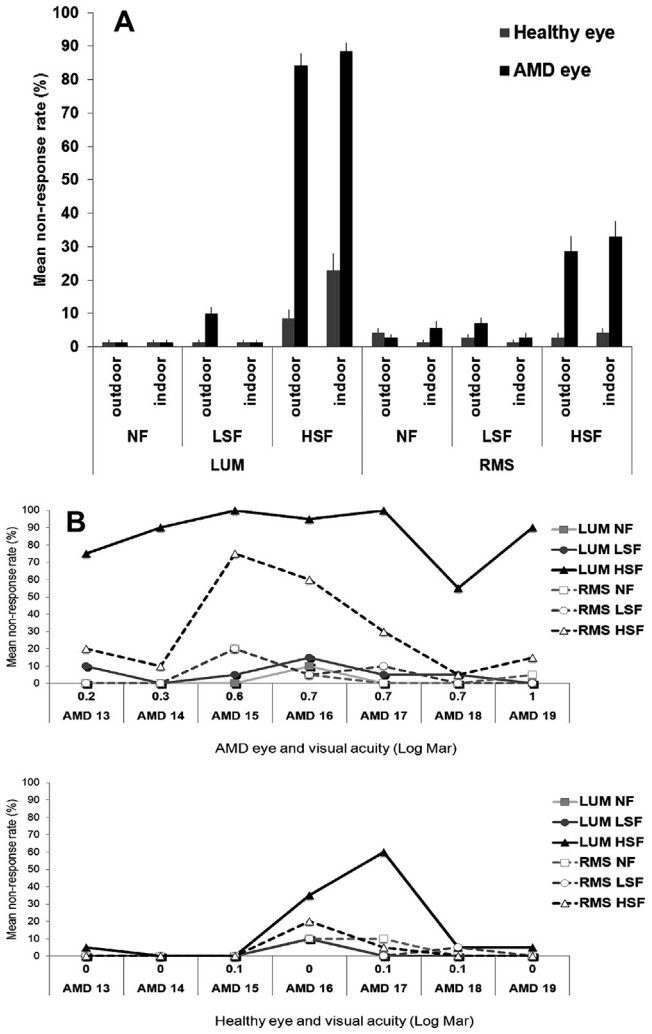

Fig. 3. (A) Mean non-response rates (%) for the categorization of non-filtered scenes (NF), low-spatial frequency scenes (LSF), and high-spatial frequency scenes (HSF) for the AMD eye and healthy eye of patients. Error bars correspond to the standard error. (B) Individual results for AMD patients. (B) Individual results for AMD patients.

the 7 patients have a higher NR rate for HSF than LSF and NF scenes in both LUM and RMS0.1 conditions on their AMD eye. On their healthy eye, 5 out of the 7 patients have a higher NR rate for HSF scenes in the LUM condition and 2 out of the 7 patients for the RMS0.1 condition.

Finally, the ANOVA on mFC did not reveal an effect of Eye ($F_{1,6} < 1$). Neither the Eye × Spatial frequency interaction ($F_{2,12} < 1$) nor the Eye × Spatial frequency × Contrast interaction ($F_{2,12} = 3.29$, $p = 0.10$) were significant.

2.2.3. Unilateral AMD vs. bilateral AMD

We also investigated the effect of the severity of AMD by comparing performance between patients with unilateral AMD (11 patients) and bilateral AMD (8 patients). Two 2 × 2 × 3 × 2 analyses of variance (ANOVA) for repeated measures (with Greenhouse-Geisser correction for non-sphericity) were conducted on mean non-response rate (mNR) and mean false categorization rate (mFC) with Severity of AMD (unilateral and bilateral) as between-subjects factor, and Contrast (LUM and RMS0.1), Spatial frequency (NF, LSF, and HSF), and Category (indoor and outdoor) as within-subjects factors. Mean comparisons were explored using Tukey post hoc tests. The significant level of tests was set at 0.05.

For mNR, there was no main effect of the Severity ($F_{1,17} = 1.50$, $p = 0.24$), no Severity × Spatial frequency ($F_{2,34} = 1.18$, $p = 0.30$), and no Severity × Spatial frequency × Contrast interaction ($F_{2,34} < 1$). Similarly, for mFC, there was no main effect of the Severity ($F_{1,17} < 1$), no Severity × Spatial frequency ($F_{2,34} = 3.18$, $p = 0.06$), and no Severity × Spatial frequency × Contrast interaction ($F_{2,34} < 1$).

2.2.4. Healthy eye in AMD patients vs. controls

We finally investigated for unilateral AMD patients whether the pathology could influence the spatial frequency processing of the healthy eye by comparing performances between the healthy eye of unilateral AMD patients (7 patients) and the one of controls (12 patients). Two 2 × 2 × 3 × 2 analyses of variance (ANOVA) for repeated measures (with Greenhouse-Geisser correction for non-sphericity) were conducted on mean non-response rate (mNR) and mean false categorization rate (mFC) with Healthy group (AMD patients and Controls) as between-subjects factor, and Contrast (LUM and RMS0.1), Spatial frequency (NF, LSF, and HSF), and Category (indoor and outdoor) as within-subjects factors. Mean comparisons were explored using Tukey post hoc tests. The significant level of tests was set at 0.05.

For mNR, there was no main effect of the Healthy group ($F_{1,17} = 1.82$, $p = 0.19$), no Healthy group × Spatial frequency ($F_{2,34} = 2.61$, $p = 0.12$), and no Healthy group × Spatial frequency × Contrast interaction ($F_{2,34} = 1.72$, $p = 0.21$). For mFC, there was no main effect of the Healthy group ($F_{1,17} = 3.19$, $p = 0.09$) and no Healthy group × Spatial frequency × Contrast interaction ($F_{2,34} = 7.04$, $p = 0.06$). There was a significant Healthy group × Spatial frequency ($F_{2,34} = 7.04$, $p < 0.05$). Surprisingly, mean comparisons revealed that AMD patients using their healthy eye made more false categorization when categorizing HSF scenes (irrespective of the contrast, 5.7 ± 6.9%) than NF scenes (2.1 ± 4.2%) and LSF scenes (2.5 ± 4.4%), while there was no difference between LSF and NF scenes. It should be noted however that there were no differences between AMD patients and Controls for NSF, LSF, and HSF scenes.

3. Experiment 2

Results of Experiment 1 showed a specific HSF deficit in AMD patients even when luminance contrast was increased in HSF scene using a contrast equalization between HSF, LSF, and NF scenes. However, results revealed that a low-level contrast is also detrimental to the processing of HSF. In contrast, the categorization of LSF scenes was well preserved even when their contrast level was decreased by the contrast equalization method. In Experiment 2, we examined whether a more drastic contrast reduction could affect the categorization of NF and LSF scenes by applying a low RMS contrast corresponding to the mean contrast value of HSF scenes in their original version (i.e. RMS contrast of 0.03) to NF and LSF stimuli. We expected that if the visual deficit in scene categorization is specific to HSF, AMD patients would commit more errors than controls for HSF only. Conversely, if the visual deficit is mainly due to low luminance contrast, we expected more errors from AMD patients than controls for all stimuli.

3.1. Material and methods

3.1.1. Participants

Twelve patients with exudative AMD (five males; 69 ± 4 years; range 63–75; Table 4) who did not participate in Experiment 1 were included in the experiment. The inclusion criterion was visual acuity between 1 and 0.2 LogMAR in the most severely impaired eye. Patients were tested in only one eye. Patients with unilateral

Table 4
Demographic and clinical data of Experiment 2.

	Gender	Age (years)	Lesion type	Eye test	Visual acuity (LogMAR)		Gender	Age (years)	Visual acuity (LogMAR)
AMD 1	F	70	Unilateral	Right	0.3	Control 1	M	60	0
AMD 2	F	64	Unilateral	Left	0.3	Control 2	F	62	0
AMD 3	M	70	Bilateral	Right	0.4	Control 3	F	63	0
AMD 4	M	72	Bilateral	Left	0.4	Control 4	M	63	0
AMD 5	M	75	Bilateral	Left	0.4	Control 5	M	66	0
AMD 6	M	63	Unilateral	Right	0.6	Control 6	M	67	0
AMD 7	F	66	Bilateral	Right	0.6	Control 7	F	67	0
AMD 8	F	67	Bilateral	Left	0.6	Control 8	M	68	0
AMD 9	M	64	Bilateral	Right	0.6	Control 9	F	68	0
AMD 10	F	70	Unilateral	Right	0.6	Control 10	M	61	0.1
AMD 11	F	73	Bilateral	Right	0.6	Control 11	F	65	0.1
AMD 12	F	66	Unilateral	Right	0.8	Control 12	F	72	0.1

Table 5
mNR (%) and mFC (%), and SD for categorizing NF, LSF, and HSF outdoor and indoor scenes normalized with low RMS contrast of 0.03 in normally sighted participants and AMD patients in Experiment 2.

		RMS0.03					
		NF		LSF		HSF	
		Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor
Control	mNR	0.8	1.7	0.8	0.8	3.3	5.0
	SD	*2.9*	*3.9*	*2.9*	*2.9*	*6.5*	*8.0*
	mFC	0.8	0.8	2.5	0.8	4.2	2.5
	SD	*2.9*	*2.9*	*4.5*	*2.9*	*5.1*	*8.7*
AMD	mNR	1.7	5.0	8.3	9.2	83.3	83.3
	SD	*3.9*	*11.7*	*9.4*	*12.4*	*24.2*	*13.7*
	mFC	2.5	2.5	2.5	1.7	0.8	6.7
	SD	*4.5*	*6.2*	*4.5*	*3.9*	*2.9*	*7.8*

AMD were tested in their pathological eye. Patients with bilateral AMD were tested in the eye with the best-corrected visual acuity. Twelve normally sighted elderly participants (six males; 65 ± 3 years; range 60–72; Table 4) were also tested unilaterally, in the eye with the best-corrected visual acuity (Control group). The inclusion criterion for controls was visual acuity between 0.2 and 0 LogMAR in the selected eye. Participants with psychiatric, neurological, and ocular (glaucoma and multiple sclerosis) disorders were not included in the study, and all participants gave their informed written consent before participating in the study.

3.1.2. Stimuli and procedure

Stimuli were built from the same 20 black and white photographs of indoor and outdoor scenes used in Experiment 1. As in Experiment 1, LSF and HSF stimuli were created for each scene. The spatial frequency content of scenes was not modified for NF stimuli. The resulting images were then normalized to obtain a mean luminance of 0.5 and an RMS contrast of 0.03, corresponding to the mean standard deviation of HSF scene luminance before contrast normalization. This resulted in 3 versions of each scene. The procedure was the same as in Experiment 1. The experiment consisted of 60 trials. In one half of the trials the scene was indoor, and in the other half, the scene was outdoor. This resulted in 10 trials for each of the 6 experimental conditions: RMS0.03-NF-indoor, RMS0.03-NF-outdoor, RMS0.03-LSF-indoor, RMS0.03-LSF-oudoor, RMS0.03-HSF-indoor, and RMS0.03-HSF-outdoor. The experiment lasted about 5 min.

3.2. Results

Performances (mNR and mFC) for AMD patients and control participants are reported in Table 5. Two 2 × 3 × 2 analyses of variance (ANOVA) for repeated measures (with Greenhouse-Geisser correction for non-sphericity) were conducted on mean non-response rate (mNR) and mean false categorization rate (mFC) with

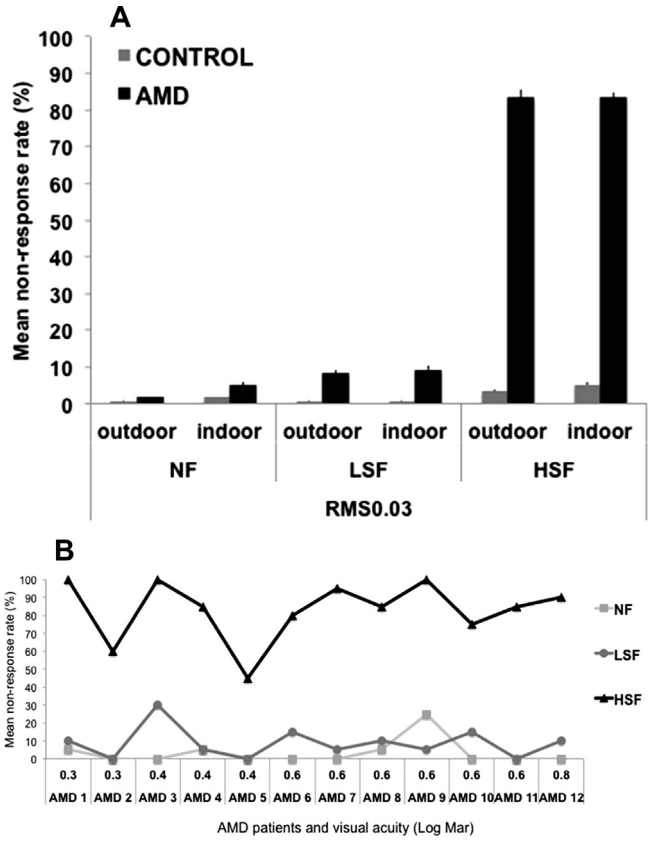

Fig. 4. Mean non-response rates (%) for the categorization of non-filtered scenes (NF), low-spatial frequency scenes (LSF), and high-spatial frequency scenes (HSF) for AMD patients and normally sighted elderly participants (Control). Error bars correspond to the standard error.

Group (AMD patients and Controls) as between-subjects factor, and Spatial frequency (NF, LSF, and HSF) and Category (indoor and outdoor) as within-subjects factors. Mean comparisons were explored using Tukey post hoc tests. The significant level of tests was set at 0.05.

The ANOVA on mNR (Fig. 4a) revealed that AMD patients responded less often than Controls (Mean ± SD: 31.8 ± 12.5% and 2.1 ± 4.5%, respectively; $F_{1,22} = 126.76$, $p < 0.001$). The Group × Spatial frequency interaction was significant ($F_{2,44} = 201.00$, $p < 0.001$). Mean comparisons revealed that AMD patients responded less often when categorizing HSF scenes (83.3 ± 19.0%) than NF scenes (3.3 ± 7.8%) and LSF scenes (8.8 ± 10.9%), while there was no difference between LSF and NF scenes. For Controls, there was no effect of spatial frequencies (NF: 1.3 ± 3.4%; LSF: 0.8 ± 2.9%; HSF: 4.2 ± 7.2%). In addition, AMD patients responded less often than Controls for HSF scenes only. The Group × Spatial frequency × Category interaction was not significant ($F_{2,12} < 1$). It should be noted that the correlation between visual acuity of AMD patients and mNR was not significant for HSF outdoor scenes ($r = -0.05$, $p = 0.89$) and HSF indoor scenes ($r = 0.17$, $p = 0.61$), and that the correlation between age of AMD patients and mNR was not significant for HSF outdoor scenes ($r = -0.21$, $p = 0.52$) and HSF indoor scenes ($r = -0.31$, $p = 0.32$). Furthermore, descriptive analysis on single participant data (Fig. 4b) showed that all patients have a higher NR rate for HSF than LSF and NF scenes.

Finally, the ANOVA on mFC did not show an effect of Group ($F_{1,22} < 1$). The Group × Spatial frequency interaction was not significant ($F_{2,44} < 1$). The Group × Spatial frequency × Category was not significant ($F_{2,44} = 2.31$, $p = 0.13$).

4. Experiment 3

Results of Experiment 1 revealed that increasing contrast in HSF scenes could improve the performances of AMD patients. In Experiment 3, we directly examined whether contrast increase could improve categorization of HSF scenes in the residual vision of AMD patients by manipulating four levels of linearly-increasing RMS contrasts (0.05, 0.10, 0.15, and 0.20).

4.1. Material and methods

4.1.1. Participants

Fourteen patients with exudative AMD who did not participate in Experiments 1 and 2 (six males; 78 ± 11 years; range 63–89; Table 6) were included in the experiment. The inclusion criterion was visual acuity between 1 and 0.2 LogMAR in the most severely impaired eye. Patients were tested in only one eye. Patients with unilateral AMD were tested in their pathological eye. Patients with bilateral AMD were tested in the eye with the best-corrected visual acuity. Fourteen normally sighted elderly participants (seven males; 65 ± 4 years; range 60–72; Table 6) were also tested unilaterally, only in the eye with the best-corrected visual acuity (Control group). The inclusion criterion for controls was visual acuity between 0.2 and 0 LogMAR in the selected eye. Participants with psychiatric, neurological, and ocular (glaucoma and multiple sclerosis) disorders were not included in the study, and all participants gave their informed written consent before participating in the study.

4.1.2. Stimuli and procedure

Stimuli were built from the same 20 black and white photographs of indoor and outdoor scenes used in Experiments 1 and 2. As in Experiment 1, a HSF stimulus was created for each scene. The resulting images were normalized to obtain a mean luminance of 0.5. HSF scenes were then normalized using four different levels of linearly-increasing RMS contrast (RMS contrast of 0.05, 0.10, 0.15, and 0.20). Contrast values were situated between LSF and HSF contrast values in natural conditions (i.e. 0.21 and 0.03, respectively in the LUM condition). This resulted in 4 versions of each scene. It should be noted that the scenes normalized with an RMS contrast of 0.01 were the same as the ones used in Experiment 1. The procedure was the same as in Experiments 1 and 2. The experiment consisted of 80 trials. In one half of the trials the scene was indoor, and in the other half, the scene was outdoor. This resulted in 10 trials for each of the 8 experimental conditions: RMS0.05-HFS-indoor, RMS0.05-HFS-outdoor, RMS0.1-HFS-indoor, RMS0.1-HFS-outdoor, RMS0.15-HFS-indoor, RMS0.15-HFS-outdoor, RMS0.2-HFS-indoor, and RMS0.2-HFS-outdoor. The experiment lasted about 7 min.

4.2. Results

Performances (mNR and mFC) for AMD patients and controls are reported in Table 7. The mFC was very low and showed a ceiling effect with no variance, even for patients in the RMS0.2 conditions (i.e. 0% of global errors). Thus, analyses were conducted on mean global error rate (mER, i.e. mNR and mFC taken together). Firstly, given that the mER for categorizing HSF scenes in controls was again very low even in the RMS0.05 condition and showed a ceiling effect with no variance in several experimental conditions, we used controls' performances as a norm and we tested the mean percentage scores of AMD patients against this norm for each condition by conducting one-sample Student *t* tests. Results showed that AMD patients made more errors for all experimental conditions, excepted for outdoor HSF scenes of the RMS0.15 and RMS0.2 conditions.

Table 6
Demographic and clinical data of Experiment 3.

	Gender	Age (years)	Lesion type	Eye test	Visual acuity (LogMAR)		Gender	Age (years)	Visual acuity (LogMAR)
AMD 1	F	67	Unilateral	Left	0.3	Control 1	M	60	0
AMD 2	F	74	Unilateral	Left	0.3	Control 2	F	61	0
AMD 3	M	86	Bilateral	Right	0.3	Control 3	F	61	0
AMD 4	F	87	Bilateral	Right	0.3	Control 4	F	63	0
AMD 5	F	89	Bilateral	Right	0.3	Control 5	M	63	0
AMD 6	M	82	Bilateral	Left	0.4	Control 6	F	66	0
AMD 7	M	85	Bilateral	Left	0.4	Control 7	M	67	0
AMD 8	M	63	Unilateral	Right	0.6	Control 8	F	67	0
AMD 9	F	66	Bilateral	Right	0.6	Control 9	F	68	0
AMD 10	F	67	Bilateral	Left	0.6	Control 10	F	68	0
AMD 11	M	74	Bilateral	Right	0.6	Control 11	M	61	0.1
AMD 12	M	80	Unilateral	Right	0.6	Control 12	M	62	0.1
AMD 13	F	83	Bilateral	Right	0.6	Control 13	M	66	0.1
AMD 14	F	66	Unilateral	Right	0.8	Control 14	M	72	0.2

Table 7
mNR (%) and mFC (%), and SD for categorizing HSF outdoor and indoor scenes normalized with RMS contrast of 0.05, 0.1, 0.15, and 0.2 in healthy elderly participants and AMD patients in Experiment 3.

		HSF-RMS0.05		HSF-RMS0.1		HSF-RMS0.15		HSF-RMS0.2	
		Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor
Control	mNR	0.7	1.4	0	0	0	0	0	0
	SD	*2.7*	*3.6*	*0*	*0*	*0*	*0*	*0*	*0*
	mFC	0.7	2.1	0.7	0.7	0	0	0.7	0
	SD	*2.7*	*4.2*	*2.7*	*2.7*	*0*	*0*	*2.7*	*0*
AMD	mNR	67.9	61.4	12.9	23.6	2.9	10.0	2.9	6.4
	SD	*26.1*	*24.1*	*12.0*	*19.8*	*6.1*	*10.4*	*4.7*	*9.3*
	mFC	2.9	5.7	0.7	2.9	0.7	3.6	0	2.9
	SD	*6.1*	*8.5*	*2.7*	*6.1*	*2.7*	*5.0*	*0*	*6.1*

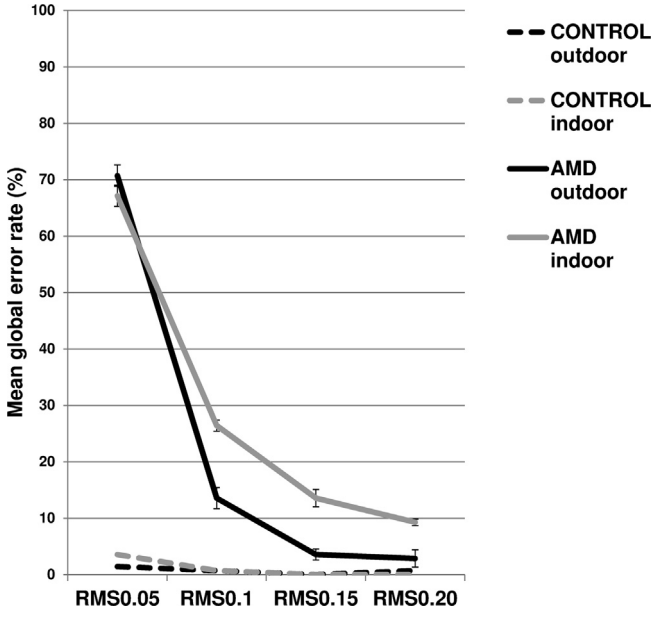

Fig. 5. Mean global error rates (%) for the categorization of high-spatial frequency scenes (HSF) for the AMD patients and normally sighted elderly participants (Control). Error bars for AMD patients correspond to the standard error.

Then, one 4 × 2 analyses of variance (ANOVA) for repeated measures (with Greenhouse-Geisser correction for non-sphericity) was conducted on mER of patients with RMS contrast (0.05, 0.10, 0.15, and 0.20) and Category (indoor and outdoor) as within-subjects factors. Mean comparisons were explored using Tukey post hoc tests. The significant level of tests was set at 0.05.

The ANOVA revealed a significant effect of Contrast ($F_{3,39} = 98.92$, $p < 0.001$) and the Category interacted with the Contrast of HSF scenes ($F_{3,39} = 4.68$, $p < 0.05$). Mean comparisons revealed that AMD patients made more errors for a RMS contrast of 0.20 and 0.15 than 0.10 and 0.05, and they made also more errors for 0.10 than 0.05. There was no difference between 0.20 and 0.15. The same pattern of results was observed for outdoor and indoor scenes separately (Fig. 5). Finally, mean comparisons revealed that AMD patients made more errors for HSF outdoors than HSF indoors for the RMS contrasts of 0.10, 0.15 and 0.20. Descriptive analysis on single participant data showed systematic performance improvement from 0.10 to 0.05 for all patients.

5. General discussion

The primary aim of the present study was to investigate the processing of spatial frequencies in AMD patients. Overall, Experiments 1 and 2 revealed that AMD patients made more errors (in fact, non-responses) in the categorization of HSF than of LSF scenes, irrespective of the luminance contrast level. In addition, they made more errors when categorizing scenes on the basis of HSF information than healthy elderly participants, irrespective of the luminance contrast level of scenes. In an original way, Experiment 1 also revealed that patients with unilateral AMD, tested in both eyes individually, made more non-responses when categorizing HSF scenes using their AMD eye than when using their healthy eye. The deficit observed in AMD patients for processing HSF in large scene is consistent with the contrast sensitivity decrease for HSF in sinusoidal gratings (Brown & Lovie-Kitchin, 1988; Kleiner et al., 1988; Midena et al., 1997). Brown and Lovie-Kitchin (1988) investigated the contrast sensitivity function at the fovea, and also at 10° in the paracentral retina of AMD patients. They observed that contrast sensitivity systematically decreased for gratings of 0.5, 1, 2, and 4 cpd at an eccentricity of 10°. It should be noted that the 8 cpd grating was omitted at an eccentricity of 10° due to the difficulty of the task. Therefore, contrast sensitivity functions have been rarely measured above 10° in the peripheral visual field of AMD patients. Given the average 4 mm lesion size in AMD patients (Cheung & Legge, 2005) that approximately corresponds to a lesion sized 13° of visual angle, Brown and Lovie-Kitchin (1988) results suggest that contrast-sensitivity tests are not suitable to investigate the visual abilities of AMD patients to process spatial frequency information in their considered to be unaffected peripheral visual field.

Our results showed that the categorization of NF and LSF scenes was well preserved in both experiments. According to the literature, the information conveyed by LSF is sufficient to categorize complex scenes (Torralba & Oliva, 2003). Tran, Rambaud, Despretz, and Boucart (2010) showed that AMD patients were able to categorize large non-filtered indoor and outdoor scenes using their peripheral vision. Thibaut, Tran, Szaffarczyk, and Boucart (2014) observed that AMD patients were also able to categorize non-filtered scenes in their peripheral vision at an eccentricity of 12°. According to the authors, low spatial resolution of peripheral vision (i.e. LSF information) allowed these patients to accomplish the task. Our study demonstrated that LSF information below 24 cycles per image allows efficient categorization of large scenes (24 × 18 degrees) in AMD patients, and indicated that when this information is available in the residual vision of patients, this preserved ability can be used to categorize scenes. Alternatively, LSF information may be more critical than HFS information for categorizing scenes as indoors or outdoors. Indeed, even if normal visual inputs in the real world usually contain both LSF and HSF information, there is considerable experimental evidence of a flexible usage of spatial frequency information (Morrison & Schyns, 2001; Schyns, 1998). Recognition depends on the object spatial frequency information and retinal spatial frequency available (Gold, Bennett, & Sekuler, 1999; Näsänen, 1999; Parish & Sperling, 1991, for face and letter stimuli), in central and peripheral vision (Kwon &

Legge, 2011), but also on the task requirements (e.g., categorization of gender vs. emotional expressions in faces, Schyns & Oliva, 1999; emotional appraisal vs. tendency to action in emotional scenes, Campagne et al., 2016; Fradcourt, Peyrin, Baciu, & Campagne, 2013), the level of categorization (e.g., basic vs. superordinate, see Harel & Bentin, 2009), as well as the type of comparison (e.g., house-flower vs. face-house vs. flower-face, see Rotshtein et al., 2010). Schyns and Oliva (1999), for instance, showed that HSF information is preferentially used for deciding whether a face is expressive or not, whereas LSF information is preferred to determine the nature of the emotion (e.g., happy, angry). Consistently with an impaired processing of HSF in AMD patients, Boucart, Dinon, et al. (2008) showed that AMD patients failed at deciding whether a non-filtered face was expressive or not. These results highlighted the importance of assessing the spatial frequency processing of AMD patients using complex visual stimuli and natural tasks.

Musel et al. (2011) previously investigated the categorization of indoor and outdoor filtered scenes (LSF and HSF) in AMD patients. As in the present study, results showed that AMD patients gave more non-responses when categorizing HSF than LSF scenes, whereas no difference was observed between spatial frequencies in normally sighted participants. The HSF deficit in AMD patients could be interpreted as a consequence of their central retinal lesion. AMD is a retinal disease that leads to the loss of photoreceptors in the central area of the macula (fovea). The density of cones and midget ganglion cells, which are used for processing HSF information, is greatest in the center of the retina. Furthermore, the distribution of retinal photoreceptors and ganglion cells is not homogenous (Curcio, Sloan, Kalina, & Hendrickson, 1990), the density of cones and midget ganglion cells decreases with retinal eccentricity. Receptive fields are larger in the parafoveal retina. Patients with central scotoma therefore have to use their parafoveal vision when dealing with lower spatial resolution, and this might result in the loss or misrepresentation of HSF information. Alternatively, the results reported in our study could be predicted by visual acuity or resolution limit alone. Indeed, the mean visual acuity of all patients was about 0.50 log MAR, equivalent to about 10 cpd resolution limit. With a spatial frequency cut-off of 6 cpd, HSF scenes are thus under the resolution limit. Correlation analysis did not show any relationship between patients' performance during the processing of HSF information and their visual acuity, limiting interpretation of the results in terms of average resolution limit.

In the present study, normally sighted participants' performance was not differentially affected by the spatial frequency content of scenes. Similar results were observed by Musel et al. (2011). However, Ramanoel et al. (2015) recently investigated age-related differences in spatial frequency processing during scene categorization in normally-sighted people, and revealed performance degradation in elderly participants (over the age of 60) compared to young participants only when categorizing HSF scenes. This selective deficit in the categorization of HSF scenes even in normally sighted elderly people is consistent with the decline of visual acuity with age (Brown & Lovie-Kitchin, 1993; Elliott, Yang, & Whitaker, 1995; Gittings & Fozard, 1986; Rubin et al., 1997), and the decrease in contrast sensitivity for HSF previously observed in studies using sinusoidal gratings (Elliott, 1987; Eliott, Whitaker, & MacVeigh, 1990; Higgings, Jaffe, Caruso, & deMonasterio, 1988; Owsley, 2011; Owsley, Sekuler, & Siemsen, 1983; see however, Sekuler, Hutman, & Owsley, 1980) and could be linked to the functional decline of the parvocellular pathway in normal aging (Elliott & Werner, 2010). The fact that we did not observe a HSF deficit in normally sighted participants in the present study could be due to a number of methodological factors. Our paradigm was constructed in order to allow categorization of scenes by AMD patients, but also to avoid any bias in spatial frequency processing for normally sighted participants. Presentation time was longer (300 ms in the present study vs. 100 ms in Ramanoel et al., 2015) and this favoured HSF processing. No backward mask (1/f white noise) was displayed immediately after scenes in order to avoid retinal persistence, and participants gave automatic verbal responses instead of complex motor responses.

Ramanoel et al. (2015) conducted a control behavioral study to verify that the specific HSF deficit in normally sighted elderly participants did not result from a lower contrast in HSF scenes. As in the present study, the luminance contrast of LSF and HSF scenes was equalized using RMS contrast normalization, reducing contrast in LSF while enhancing HSF contrast. Results revealed that the categorization of HSF scenes was improved by enhancing contrast. Based on this observation, the second aim of the present study was to examine the effect of contrast on the categorization of HSF scenes by AMD patients. In Experiments 1 and 2, luminance contrast was equalized between NF, LSF, and HSF scenes using RMS contrast normalization. In Experiment 1, we used a value situated between LSF and HSF contrast in natural conditions (LUM condition), in order to avoid affecting one spatial frequency condition more than another. In this RMS0.1 condition, the contrast normalization reduces contrast in LSF while enhancing HSF contrast. Results showed that AMD patients (or AMD eye) made more non-responses for HSF than NF and LSF scenes in the RMS0.1 condition. This is consistent with an HSF deficit. However, luminance contrast value interacted with spatial frequency processing. The difference in performance between LSF and HSF categorization was smaller in the RMS0.1 condition than in the LUM condition. Importantly, the non-response rate was lower for the more highly-contrasted HSF scenes in the RMS0.1 condition than the HSF scenes in the LUM condition (and more particularly for outdoor scenes), while there was no difference between the lower-contrast LSF scenes in the RMS0.1 condition and LSF scenes in the LUM condition. This result suggests that increasing contrast in HSF scenes could improve the processing of HSF information in AMD patients, but also that low luminance contrast partially accounts for their HSF deficit in natural conditions. Therefore, Experiment 2 aimed to further explore the extent to which low luminance contrast affected the processing of spatial frequencies. We applied a low RMS contrast corresponding to the mean contrast value of original HSF scenes to NF and LSF scenes. Results showed that, in this RMS0.03 condition, AMD patients made more non-responses than normally sighted participants in the categorization of HSF scenes only. Low contrast seems to be detrimental only when the categorization of scenes is based on HSF information. Finally, in Experiment 3, we directly examined whether contrast enhancement of HSF information could improve the categorization of scenes by manipulating four levels of linearly-increasing RMS contrasts. Results showed that AMD patients' performances improved as a function of contrast, until they performed normally for outdoor scenes from an RMS contrast of 0.15. We observed a greater improvement for outdoor than for indoor scenes. In the present study, outdoor scenes are views of buildings with sky at the top and outdoor-relevant objects (e.g., car, tree). Indoor scenes are kitchens, offices and living rooms with indoor relevant objects (e.g., table, sofa, chair, etc.). Even if outdoor and indoor scenes were equivalent in terms of visual cluttering, outdoor scenes are characterized by permanent landmarks or global spatial invariants such as a building with the sky at the top and few outdoor-relevant objects in peripheral vision. In contrast, indoor-relevant objects are numerous and various, scattered all over the scene, even at the top of the peripheral visual field. Our set of scene stimuli suggests that contrast enhancement could facilitate the detection of global spatial invariants in HSF outdoor scenes in addition to the recognition of objects in the peripheral vision.

Finally, the study revealed one very intriguing result. In Experiment 1, performance in the healthy eye of patients with unilateral AMD differed from performance in the healthy eye of control participants. AMD patients made more false categorizations when categorizing HSF scenes than NF and LSF scenes, while there was no difference between spatial frequencies for controls. This result suggests that the loss of vision in the AMD eye has a negative impact on the processing of visual information in the healthy eye. Alternatively, these results could be due to eye anomalies not yet visible in the visual field (visual acuity examination), and they should be considered for early diagnosis of AMD.

6. Conclusion

The present study revealed firstly that the categorization of NF and LSF scenes was well preserved in AMD patients, even for low-contrast scenes. Residual vision of AMD patients is sufficient to categorize scenes on the basis of LSF information (i.e. for NF and LSF scenes). Furthermore, our findings point to a deficit in AMD patients in the categorization of HSF scenes. Even if we do not directly see HSF images in the everyday life, we have constantly to deal with this content, even in parafoveal vision, especially for fine visual discrimination and detailed visual perception, as well as for the execution of natural actions. Many everyday activities, such as cooking, mobility, driving and so on, require identifying objects, finding objects or using tools, even in periphery. An efficient processing of details information, based on HSF, in peripheral vision becomes even more important after central vision loss. For example, walking down the stairs constitute a serious handicap for AMD patient mobility. The patients' ability to identify a handrail or the stairs with their peripheral vision is critical. Therefore, an efficient detailed perception in periphery could be very useful to be able to detect fine useful information in periphery, but also to avoid obstacles. Our results suggest that the perception of details in scene could be improved by increasing contrast in the residual peripheral vision of AMD patients. Contrast and contour enhancement methods have been developed to improve image and video perception in the residual peripheral vision of low vision patients (Fullerton & Peli, 2008; Kwon et al., 2012; Luo, Satgunam, & Peli, 2012; Peli & Woods, 2009; Satgunam et al., 2012; for a review, see Moshtael, Aslam, Underwood, & Dhillon, 2015). For example, searching for an object in scene image in peripheral vision benefits from image enhancement for normally sighted elderly people with simulated central field loss (Kwon et al., 2012) and patients with low vision impairment (including AMD, Luo et al., 2012). Image enhancement technology is suitable for image or video displays, but less easily for mobile use. It has been shown that glasses with yellow filter lenses improve the contrast sensitivity of AMD patients (Langagergaard, Ganer, & Baggesen, 2003). In normally sighted participants, Lenoble, Boucart, Rougier, Bordaberry, and Delord (2014) showed that yellow filter lenses improve the speed of categorization of objects (sized 5.2°) displayed peripherally (at 21° eccentricity). Thus, increasing the contrast of the whole scene (both LSF and HSF) using filter lenses would a priori not be beneficial for the perception of global forms in scenes, but it could facilitate the detection of objects and details in residual vision (e.g., the first step of a staircase). Future studies may wish to examine the potential yellow filter effect on the categorization of HSF scenes.

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References

Bex, P. J., & Makous, W. (2002). Spatial frequency, phase, and the contrast of natural images. *Journal of the Optical Society of America A: Optics, Image Science, and Vision, 19*(6), 1096–1106.

Bordier, C., Petra, J., Dauxerre, C., Vital-Durand, F., & Knoblauch, K. (2011). Influence of background on image recognition in normal vision and age-related macular degeneration. *Ophthalmic and Physiological Optics, 31*(3), 203–215. http://dx.doi.org/10.1111/j.1475-1313.2011.00820.x.

Boucart, M., Despretz, P., Hladiuk, K., & Desmettre, T. (2008). Does context or color improve object recognition in patients with low vision? *Visual Neuroscience, 25*(5–6), 685–691. http://dx.doi.org/10.1017/S0952523808080826.

Boucart, M., Dinon, J. F., Despretz, P., Desmettre, T., Hladiuk, K., & Oliva, A. (2008). Recognition of facial emotion in low vision: A flexible usage of facial features. *Visual Neuroscience, 25*(4), 603–609. http://dx.doi.org/10.1017/S0952523808080656.

Boucart, M., Moroni, C., Despretz, P., Pasquier, F., & Fabre-Thorpe, M. (2010). Rapid categorization of faces and objects in a patient with impaired object recognition. *Neurocase, 16*(2), 157–168. http://dx.doi.org/10.1080/13554790903339637.

Brown, B., & Lovie-Kitchin, J. E. (1988). Contrast sensitivity in central and paracental retina in age related maculopathy. *Clinical and Experimental Optometry, 70*, 145–148.

Brown, B., & Lovie-Kitchin, J. (1993). Repeated visual acuity measurement: Establishing the patient's own criterion for change. *Optometry and Vision Science, 70*(1), 45–53. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8430008.

Bullimore, M. A., Bailey, I. L., & Wacker, R. T. (1991). Face recognition in age-related maculopathy. *Investigative Ophthalmology & Visual Science, 32*(7), 2020–2029.

Campagne, A., Fradcourt, B., Pichat, C., Baciu, M., Kauffmann, L., & Peyrin, C. (2016). Cerebral correlates of emotional and action appraisals during visual processing of emotional scenes depending on spatial frequency: A pilot study. *PLoS One, 11*(1), e0144393. http://dx.doi.org/10.1371/journal.pone.0144393.

Cheung, S. H., & Legge, G. E. (2005). Functional and cortical adaptations to central vision loss. *Visual Neuroscience, 22*(2), 187–201. http://dx.doi.org/10.1017/S0952523805222071.

Curcio, C. A., Sloan, K. R., Kalina, R. E., & Hendrickson, A. E. (1990). Human photoreceptor topography. *The Journal of Comparative Neurology, 292*(4), 497–523. http://dx.doi.org/10.1002/cne.902920402.

Elliott, D. B. (1987). Contrast sensitivity decline with ageing: A neural or optical phenomenon? *Ophthalmic and Physiological Optics, 7*(4), 415–419.

Elliott, S. L., & Werner, J. S. (2010). Age-related changes in contrast gain related to the M and P pathways. *Journal of Vision, 10*(4), 4.1–4.15. http://dx.doi.org/10.1167/10.4.4.

Elliott, D., Whitaker, D., & MacVeigh, D. (1990). Neural contribution to spatiotemporal contrast sensitivity decline in healthy ageing eyes. *Vision Research, 30*(4), 541–547.

Elliott, D. B., Yang, K. C., & Whitaker, D. (1995). Visual acuity changes throughout adulthood in normal, healthy eyes: seeing beyond 6/6. *Optometry and Vision Science, 72*(3), 186–191.

Field, D. J. (1987). Relations between the statistics of natural images and the response properties of cortical cells. *Journal of the Optical Society of America A: Optics, Image Science, and Vision, 4*(12), 2379–2394.

Fine, E. M., & Peli, E. (1995). Scrolled and rapid serial visual presentation texts are read at similar rates by the visually impaired. *Journal of the Optical Society of America A: Optics, Image Science, and Vision, 12*(10), 2286–2292. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/7500210.

Fletcher, D. C., Schuchard, R. A., & Watson, G. (1999). Relative locations of macular scotomas near the PRL: Effect on low vision reading. *Journal of Rehabilitation Research and Development, 36*(4), 356–364.

Fradcourt, B., Peyrin, C., Baciu, M., & Campagne, A. (2013). Behavioral assessment of emotional and motivational appraisal during visual processing of emotional scenes depending on spatial frequencies. *Brain and Cognition, 83*(1), 104–113. http://dx.doi.org/10.1016/j.bandc.2013.07.009.

Fullerton, M., & Peli, E. (2008). Digital enhancement of television signals for people with visual impairments: Evaluation of a consumer product. *Journal of Society for Information Display, 16*(3), 493–500.

Gittings, N. S., & Fozard, J. L. (1986). Age related changes in visual acuity. *Experimental Gerontology, 21*(4–5), 423–433.

Gold, J., Bennett, P. J., & Sekuler, A. B. (1999). Identification of band-pass filtered letters and faces by human and ideal observers. *Vision Research, 39*(21), 3537–3560.

Harel, A., & Bentin, S. (2009). Stimulus type, level of categorization, and spatial-frequencies utilization: Implications for perceptual categorization hierarchies. *Journal of Experimental Psychology: Human Perception and Performance, 35*(4), 1264–1273. http://dx.doi.org/10.1037/a0013621.

Hassan, S. E., Lovie-Kitchin, J. E., & Woods, R. L. (2002). Vision and mobility performance of subjects with age-related macular degeneration. *Optometry and Vision Science, 79*(11), 697–707.

Higgins, K. E., Jaffe, M. J., Caruso, R. C., & deMonasterio, F. M. (1988). Spatial contrast sensitivity: Effects of age, test-retest, and psychophysical method. *Journal of the Optical Society of America A: Optics, Image Science, and Vision, 5*(12), 2173–2180.

Kauffmann, L., Ramanoel, S., Guyader, N., Chauvin, A., & Peyrin, C. (2015). Spatial frequency processing in scene-selective cortical regions. *Neuroimage, 112*, 86–95. http://dx.doi.org/10.1016/j.neuroimage.2015.02.058.

Kleiner, R. C., Enger, C., Alexander, M. F., & Fine, S. L. (1988). Contrast sensitivity in age-related macular degeneration. *Archives of Ophthalmology, 106*(1), 55–57.

Kwon, M., & Legge, G. E. (2011). Spatial-frequency cutoff requirements for pattern recognition in central and peripheral vision. *Vision Research, 51*(18), 1995–2007.

Kwon, M., Ramachandra, C., Satgunam, P., Mel, B. W., Peli, E., & Tjan, B. S. (2012). Contour enhancement benefits older adults with simulated central field loss. *Optometry and Vision Science, 89*(9), 1374–1384.

Langagergaard, U., Ganer, H. J., & Baggesen, K. (2003). Age-related macular degeneration: Filter lenses help in certain situations. *Acta Ophthalmologica Scandinavica, 81*(5), 455–458.

Legge, G. E., Rubin, G. S., Pelli, D. G., & Schleske, M. M. (1985). Psychophysics of reading–II. Low vision. *Vision Research, 25*(2), 253–265.

Lenoble, Q., Boucart, M., Rougier, M. B., Bordaberry, P., & Delord, S. (2014). Does a yellow filter improve visual object categorization in normal aging? *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition, 21*(3), 325–345. http://dx.doi.org/10.1080/13825585.2013.823143.

Luo, G., Satgunam, P., & Peli, E. (2012). Visual search performance of patients with vision impairment: Effect of JPEG image enhancement. *Ophthalmic and Physiological Optics, 32*(5), 421–428.

Midena, E., Degli Angeli, C., Blarzino, M. C., Valenti, M., & Segato, T. (1997). Macular function impairment in eyes with early age-related macular degeneration. *Investigative Ophthalmology & Visual Science, 38*(2), 469–477.

Morrison, D. J., & Schyns, P. G. (2001). Usage of spatial scales for the categorization of faces, objects, and scenes. *Psychonomic Bulletin & Review, 8*(3), 454–469.

Moshtael, H., Aslam, T., Underwood, I., & Dhillon, B. (2015). High tech aids low vision: A review of image processing for the visually impaired. *Translational Vision Science & Technology, 4*(4), 6.

Musel, B., Bordier, C., Dojat, M., Pichat, C., Chokron, S., Le Bas, J. F., & Peyrin, C. (2013). Retinotopic and lateralized processing of spatial frequencies in human visual cortex during scene categorization. *Journal of Cognitive Neuroscience, 25*(8), 1315–1331. http://dx.doi.org/10.1162/jocn_a_00397.

Musel, B., Hera, R., Chokron, S., Alleysson, D., Chiquet, C., Romanet, J. P., ... Peyrin, C. (2011). Residual abilities in age-related macular degeneration to process spatial frequencies during natural scene categorization. *Visual Neuroscience, 28*(6), 529–541. http://dx.doi.org/10.1017/S0952523811000435.

Nasanen, R. (1999). Spatial frequency bandwidth used in the recognition of facial images. *Vision Research, 39*(23), 3824–3833.

Owsley, C. (2011). Aging and vision. *Vision Research, 51*(13), 1610–1622. http://dx.doi.org/10.1016/j.visres.2010.10.020.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research, 23*(7), 689–699.

Parish, D. H., & Sperling, G. (1991). Object spatial frequencies, retinal spatial frequencies, noise, and the efficiency of letter discrimination. *Vision Research, 31*(7–8), 1399–1415.

Peli, E., & Woods, R. L. (2009). Image enhancement for impaired vision: The challenge of evaluation. *International Journal on Artificial Intelligence Tools, 18*(3), 415–438.

Ramanoel, S., Kauffmann, L., Cousin, E., Dojat, M., & Peyrin, C. (2015). Age-related differences in spatial frequency processing during scene categorization. *PLoS One, 10*(8), e0134554. http://dx.doi.org/10.1371/journal.pone.0134554.

Rotshtein, P., Schofield, A., Funes, M. J., & Humphreys, G. W. (2010). Effects of spatial frequency bands on perceptual decision: it is not the stimuli but the comparison. *Journal of Vision, 10*(10), 25.

Rovner, B. W., & Casten, R. J. (2002). Activity loss and depression in age-related macular degeneration. *The American Journal of Geriatric Psychiatry, 10*(3), 305–310.

Rubin, G. S., West, S. K., Munoz, B., Bandeen-Roche, K., Zeger, S., Schein, O., & Fried, L. P. (1997). A comprehensive assessment of visual impairment in a population of older Americans. The SEE Study. Salisbury Eye Evaluation Project. *Investigative Ophthalmology & Visual Science, 38*(3), 557–568.

Salive, M. E., Guralnik, J., Glynn, R. J., Christen, W., Wallace, R. B., & Ostfeld, A. M. (1994). Association of visual impairment with mobility and physical function. *Journal of the American Geriatrics Society, 42*(3), 287–292.

Satgunam, P., Woods, R. L., Luo, G., Bronstad, P. M., Reynolds, Z., Ramachandra, C., ... Peli, E. (2012). Effects of contour enhancement on low-vision preference and visual search. *Optometry and Vision Science, 89*(9), E1364–E1373.

Schyns, P. G. (1998). Diagnostic recognition: Task constraints, object information, and their interactions. *Cognition, 67*(1–2), 147–179.

Schyns, P. G., & Oliva, A. (1999). Dr. Angry and Mr. Smile: When categorization flexibly modifies the perception of faces in rapid visual presentations. *Cognition, 69*(3), 243–265.

Sekuler, R., Hutman, L. P., & Owsley, C. J. (1980). Human aging and spatial vision. *Science, 209*(4462), 1255–1256.

Tejeria, L., Harper, R. A., Artes, P. H., & Dickinson, C. M. (2002). Face recognition in age related macular degeneration: Perceived disability, measured disability, and performance with a bioptic device. *British Journal of Ophthalmology, 86*(9), 1019–1026.

Thibaut, M., Tran, T. H., Szaffarczyk, S., & Boucart, M. (2014). The contribution of central and peripheral vision in scene categorization: A study on people with central vision loss. *Vision Research, 98*, 46–53. http://dx.doi.org/10.1016/j.visres.2014.03.004.

Torralba, A., & Oliva, A. (2003). Statistics of natural image categories. *Network, 14*(3), 391–412.

Tran, T. H., Despretz, P., & Boucart, M. (2012). Scene perception in age-related macular degeneration: The effect of contrast. *Optometry and Vision Science, 89*(4), 419–425. http://dx.doi.org/10.1097/OPX.0b013e31824c3a21.

Tran, T. H., Guyader, N., Guerin, A., Despretz, P., & Boucart, M. (2011). Figure ground discrimination in age-related macular degeneration. *Investigative Ophthalmology & Visual Science, 52*(3), 1655–1660. http://dx.doi.org/10.1167/iovs.10-6003.

Tran, T. H., Rambaud, C., Despretz, P., & Boucart, M. (2010). Scene perception in age-related macular degeneration. *Investigative Ophthalmology & Visual Science, 51*(12), 6868–6874. http://dx.doi.org/10.1167/iovs.10-5517.