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Contrast sensitivity, healthy aging and noise ☆

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ABSTRACT

At least three studies have used external noise paradigms to investigate the cause of contrast sensitivity losses due to healthy aging. These studies have used noise that was spatiotemporally localized on the target. Yet, Allard and Cavanagh (2011) have recently shown that the processing strategy can change with localized noise thereby violating the noise-invariant processing assumption and compromising the application of external noise paradigms. The present study reassessed the cause of age-related contrast sensitivity losses using spatiotemporally extended external noise (i.e., full-screen, continuously displayed dynamic noise). Contrast thresholds were measured for young (mean = 24 years) and older adults (mean = 69 years) at 3 spatial frequencies (1, 3 and 9 cpd) and 3 noise conditions (noise-free, local noise and extended noise). At the two highest spatial frequencies, the results were similar with local and extended noise: the sensitivity loss was mainly due to lower calculation efficiency. At the lowest spatial frequency, age-related contrast sensitivity losses were attributed to the internal equivalent noise when using extended noise and, like in previous studies, due to calculation efficiency with local noise. These results show that the interpretation of external noise paradigms can drastically differ depending on the noise type suggesting that external nose paradigms should use external noise that is spatiotemporally extended like internal noise to avoid triggering a processing strategy change. Contrary to previous studies, we conclude that healthy aging does not affect the calculation efficiency of the detection process at low spatial frequencies.

1. Introduction

Healthy aging affects contrast sensitivity, especially at high spatial frequencies (for a recent review, see Owsley, 2011), but the causes of this sensitivity loss are still debated. Aging could impair contrast sensitivity because the elderly have more distortions that impair the visual input (i.e., internal noise) or because they are less efficient at detecting a target embedded in internal noise (i.e., require a greater signal-to-noise ratio to detect the signal). A greater amount of noise could be due to optical factors (e.g., smaller pupil size, Loewenfeld, 1979; lens densification, Pokorny, Smith, & Lutze, 1987) or neural factors (e.g., greater spontaneous neural activity, Schmolesky et al., 2000). The efficiency to detect a target (namely, calculation efficiency) would be affected if aging affects the ability of the detection mechanism to integrate the relevant visual information. For instance, contrast sensitivity could be impaired due to lower integration of relevant information (e.g., lower spatial or temporal summation) or the integration of irrelevant information (e.g., due to spatial, temporal or frequency uncertainty).

External noise paradigms (Pelli, 1981, 1990) can be used to investigate whether age-related contrast sensitivity losses are due to internal noise or calculation efficiency. When the external noise is high, the impact of the internal noise added by the visual system becomes negligible, so contrast detection thresholds in high noise depend only on the calculation efficiency (i.e., signal-to-noise ratio required to detect the signal). The impact of the internal noise can be quantified as the amount of external noise that has the same impact as the internal distortions, namely, the internal equivalent noise. This corresponds to the knee of the contrast threshold curve when plotted as a function of noise contrast on a log–log plot (Fig. 1). Thus, more internal noise would affect contrast thresholds in low but not in high external noise (Fig. 1, left), whereas lower calculation efficiency would affect detection thresholds in both low and high external noise (Fig. 1, right). By evaluating contrast thresholds in low and high external noise, it is therefore possible to determine if an age-related sensitivity loss is due to more internal noise, lower calculation efficiency or both.

We are not the first to investigate whether age-related contrast sensitivity losses are due to higher internal equivalent noises or lower calculation efficiencies. At a low spatial frequency (1 cycle

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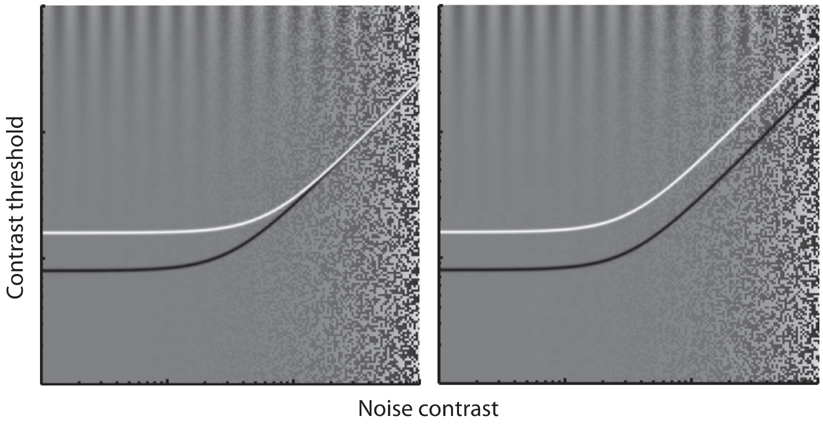

Fig. 1. Hypothetical contrast thresholds as a function of external noise contrast for young (black) and older (white) subjects. When external noise is lower than internal equivalent noise, it is negligible and performance is unaffected by its variation (flat portion of the curve). When external noise is higher than internal equivalent noise, it affects contrast thresholds (rising asymptote). If aging affects internal noise, then it would impair contrast threshold only when it is limited by internal noise (i.e., when external noise is low), but not when external noise dominates (left graph). If aging affects calculation efficiency (i.e., detection mechanisms of elderly requires greater signal-to-noise ratio), then it would impair contrast thresholds whether it is limited by internal or external noise (right graph).

per degree, cpd), many studies (Bennett, Sekuler, & Ozin, 1999; Pardhan, 2004; Speranza, Moraglia, & Schneider, 2001) found that older observers had lower calculation efficiencies but similar internal equivalent noise, suggesting that aging affects the efficiency of the detection mechanism extracting the signal from noise. At high spatial frequencies (6–10 cpd), different studies found different results. Pardhan (2004) found a significant age-related change in internal equivalent noise and no significant change in calculation efficiency, whereas Bennett, Sekuler, and Ozin (1999) and Pardhan et al. (1996) found the opposite pattern of results: a significant change in calculation efficiency and no significant change in internal equivalent noise.

An underlying assumption of external noise paradigms is that the signal is detected by the same mechanism whether thresholds are limited by internal or external noise, that is, in low and high external noise, respectively. If this assumption is valid, it is possible to measure the calculation efficiency of the detection mechanisms by adding external noise, which nulls the impact of internal noise. Previous studies have implicitly made this noise-invariant processing assumption, but Allard and Cavanagh (2011) have recently shown that it can be violated. Under some conditions, adding external noise can change a detection task to a discrimination or recognition task. The mechanisms detecting the signal in low noise (i.e., when internal noise dominates) can be different from the one "detecting" the signal in high noise. This processing strategy shift could be caused by the fact that when external noise dominates internal noise (i.e., high noise), the observer always detects something (i.e., the noise) whether the target is present or not. As a result, the observer would need to discriminate both stimuli (signal + noise vs. noise) by using a discrimination or recognition strategy (e.g., which of the two stimuli is shaped like the target?) rather than a simple detection strategy (e.g., was something presented or not?). Allard and Cavanagh (2011) observed this processing strategy shift when external noise was spatiotemporally localized to the target (i.e., appear simultaneously with the target and at the target location), but not when the external noise was spatiotemporally extended (i.e., continuously present over the entire screen). This can be explained by the fact that, with high local noise, the observer always detects something distinct from the background whether the signal was present or not (Fig. 2, middle column). However, with extended noise the task would consist in determining if a pattern can be distinguished from the noisy background (Fig. 2, right column). This would be highly similar to detecting a target embedded in internal noise (Fig. 2, left column), which should be continuously present across time and space. Thus, whether internal or extended external noise dominates, the detection task would consist in determining if a pattern can be distinguished from the noisy background.

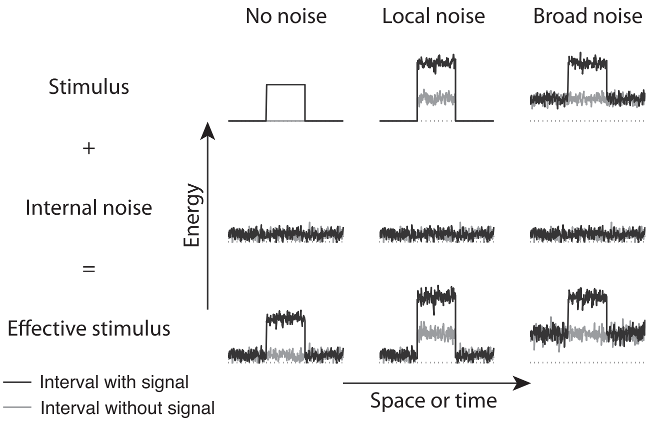

Fig. 2. Energy level when a target is present (black) or absent (gray) as a function of a given dimension (e.g., space or time) for three noise conditions: no noise (left), local noise (middle) and extended noise (right). The top row represents the energy level of the external stimulus, the middle row represents internal noise added by the visual system and the bottom row represents the effective stimulus (i.e., the external stimulus summed with internal noise). The effective stimulus of the no and extended noise conditions have similar profiles, which is different from the one with the local noise that shows an important energy variation even in the absence of a signal. This could explain why different processing strategies underlie detection in local noise. The dotted line represents the zero energy level.

The studies that investigated whether age-related contrast sensitivity losses are due to more internal noise or lower calculation efficiencies (Bennett, Sekuler, & Ozin, 1999; Pardhan, 2004; Pardhan et al., 1996; Speranza, Moraglia, & Schneider, 2001) have used local, static external noise. Thus, it is possible that in high external noise conditions they were not evaluating the calculation efficiency of the *detection* mechanism per se (i.e., detecting a signal embedded in a noisy background) as they assumed they were, but were rather measuring the efficiency of a higher-level discrimination or recognition process. The objective of the current study was to reassess whether the age-related contrast sensitivity losses at low, medium and high spatial frequencies are due to higher internal equivalent noise or lower calculation efficiency by using extended dynamic noise to avoid triggering a processing strategy shift. For comparative reasons with previous studies, we also measured the contrast thresholds in local, static noise.

2. Method

2.1. Participants

Twenty individuals aged between 20 and 29 years of age (mean age 24.3 ± 2.2 years) and twenty older adults aged between 65 and 76 years old (mean age 69.1 ± 3.5 years) participated in the study. Participants were required to have a good ocular health to be included and any subject with ocular anomalies like strabismus, amblyopia, cataract, age-related macular degeneration, glaucoma, cerebral vascular accident history or visual field dysfunctions was excluded. Best corrected monocular and binocular visual acuity were measured at distance (6 m) and at the testing distance of 2 m. All participants had a best corrected monocular and binocular visual acuity of at least 6/6 at both 2 and 6 m. All older participants had a complete visual examination done by an optometrist at the School of Optometry of Université de Montréal within the year before the experiment. The Mini-Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975) was administered to older participants prior to psychophysical evaluation. All had a score of 27/30 or higher on the MMSE, which does not suggest any obvious cognitive impairment. Informed consent was given by each participant upon evaluation. All were naïve to the purpose of the experiment and were not psychophysically experienced.

2.2. Apparatus

The stimuli were presented on a 19-in. CRT monitor with a mean luminance of 42 cd/m^2 and a refresh rate set to 60 Hz. The Noisy-Bit method (Allard & Faubert, 2008) implemented with the error of the green color gun inversely correlated with the error of the two other color guns made the 8-bit display perceptually equivalent to an analog display having a continuous luminance resolution. The monitor was the only source of light in the room. A Minolta CS100 photometer interfaced with a custom program calibrated the output intensity of each gun. At the testing distance of 2 m, there were 70 pixels per degree of visual angle.

2.3. Stimuli

Observers were asked to discriminate the orientation (horizontal or vertical) of sine wave gratings (Fig. 3). The spatial frequency of the gratings was 1, 3 or 9 cpd. The phase and orientation of the grating were randomized on each trial. The spatial window was circular with a diameter of 4 deg and soft edges following a half cosine of 1 deg. The presentation time was 500 ms plus an onset and offset half cosine ramp of 125 ms.

Noise was binary and elements were 2×2 pixels (i.e., 0.028×0.028 deg) wide. The noise rms contrasts were set to 70%, 70% and 50% for the spatial frequencies of 1, 3 and 9 cpd, respectively. Different noise contrasts were used for the different spatial frequencies so that noise contrast was high enough to substantially affect contrast thresholds at the lowest spatial frequency and enable the contrast threshold measurement at the highest spatial frequency without exceeding the 100% contrast range. For the static, local noise condition, the spatiotemporal window of the noise was the same as the one of the signal. For the dynamic, extended noise condition, the noise was resampled at 15 Hz and was presented over the entire screen and visible at all times. A feedback sound indicated the correctness of the answer.

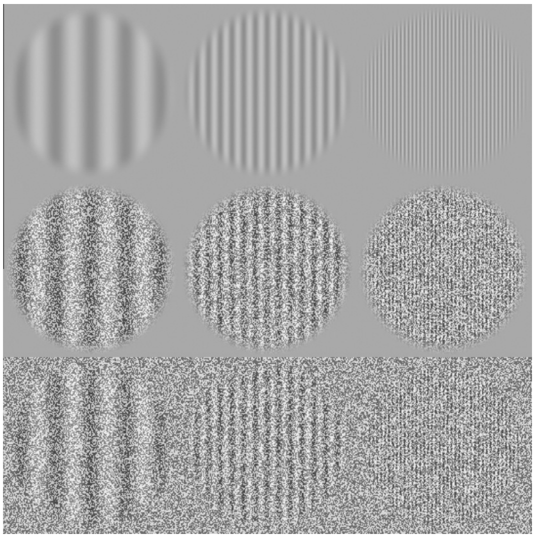

Fig. 3. Examples of vertically oriented stimuli for all 9 conditions. The spatial frequency of the gratings was 1 (left), 3 (center) or 9 (right) cpd. The noise was either absent (top), static and spatiotemporally localized (middle) or dynamic and spatiotemporally extended (bottom).

2.4. Procedure

The current study aimed at characterizing the effect of aging on the *detection* process. For practical reasons, however, we used a coarse orientation *discrimination* task (horizontal vs. vertical) instead of detection task, which we consider equivalent given that coarse discriminations are based on a single internal detection event (Pelli, Palomares, & Majaj, 2004) and coarse discrimination thresholds are just as accurate as detection thresholds (Thomas & Gille, 1979). The advantage of a discrimination task is that it is faster than a two-interval forced-choice and it does not require observers to divide their attention among spatial locations as with spatial forced-choices, which is particularly affected with aging (Sara & Faubert, 2000).

Observers verbally indicated each answer to an experimenter that inputted it by pressing one of two keyboard keys. The combination of three spatial frequencies (1, 3 and 9 cpd) and three noise conditions (no noise, static-local noise and dynamic-broad noise) resulted in 9 blocks. Each block lasted for 60 trials and a 2-down-1-up staircase procedure (Levitt, 1971) was used to control the contrast of the grating.

The first session was separated into two parts. First, observers read and signed a consent form and their acuities were measured. The MMSE was conducted for the older observers. Afterwards, we proceeded to the psychophysical experimentation. Observers had 18 practice trials at suprathreshold contrasts (two by condition). Then the 9 blocks were tested in a random order, which lasted for about 30 min. To increase the measurement precision, each observer performed a second session a few days later in which the 9 block conditions were tested twice in a pseudo-random order. Observers took a break after the first 9 blocks. The contrast threshold for each of the 9 conditions was estimated as the geometric mean of the last 6 inversions of the 3 corresponding blocks (averaging across 18 inversions).

2.5. Data fitting

The measurements of contrast threshold in absence and presence of external noise enables the calculation of the internal equivalent noise and calculation efficiency (Pelli & Farell, 1999). Contrast threshold (c) as a function of external noise contrast (σ_{ext}) is usually modeled by an equation mathematically equivalent to:

$$c(\sigma_{\text{ext}}) = \sqrt{\frac{\sigma_{\text{ext}}^2 + \sigma_{\text{int}}^2}{k}}, \tag{1}$$

where σ_{int} represents the internal equivalent noise in noise contrast units (knee point on the log–log plot as in Fig. 1) and k is proportional to the calculation efficiency. This function was used to estimate the two parameters using two threshold measurements (with and without noise) for each observer, each spatial frequency and with local or extended noise. Thus, this procedure provided, for each spatial frequency, an evaluation of the contrast sensitivity (based on the thresholds in absence of noise), an evaluation of the internal equivalent noises and calculation efficiencies using local, static noise (based on both thresholds in absence of noise and in local, static noise), and an evaluation of the internal equivalent noises and calculation efficiencies using extended, dynamic noise (based on both thresholds in absence of noise and in extended, dynamic noise).

3. Results

Fig. 4 shows the contrast sensitivity functions observed for the two age groups. Contrast sensitivity corresponded to the inverse of the contrast threshold obtained in absence of noise ($c(0)$), that is, when contrast threshold was limited by internal noise. The sensitivity of older observers was lower by a factor of 1.33, 1.29 and 1.68 at the low, medium and high spatial frequency, respectively (Fig. 1) and each of these effects was significant ($t(38) = 5.22$, 2.63 and 3.03, $p < .001$, .05 and .01, respectively). The fact that the sensitivity loss was more pronounced at the high spatial frequency is consistent with previous findings (Owsley, 2011), although this effect was not found to be significant as no frequency × age interaction was observed ($F(1.28,48.7) = 2.46$, $p = .116$).

Fig. 5 shows the calculation efficiencies measured using local, static (left) and extended, dynamic (right) noise as a function of the spatial frequency. Calculation efficiencies were calculated using Eq. (1) so they theoretically depended on the thresholds obtained in both absence and presence of noise, but since the calculation efficiency mainly depends only on thresholds in high noise, the patterns of results of contrast thresholds in high noise (not shown) and calculation efficiencies (Fig. 5) as a function of spatial frequency are nearly identical. With local, static noise, a significant calculation efficiency effect was observed at each spatial frequency ($t(38) = -3.15$, -3.45 and -3.20, $p < .01$, .01 and .01, respectively) and this effect was relatively uniform across spatial frequencies as no frequency × age interaction was observed ($F(1.27,48.2) = 1.59$, $p = .22$). Conversely, a significant frequency × age interaction was observed with dynamic, extended noise ($F(1.59,60.4) = 4.23$, $p < .05$). Specifically, an age-related effect was observed at the medium and high spatial frequencies ($t(38) = -2.04$ and -2.46, $p < .05$ and .05, respectively) and no significant effect was observed at the low spatial frequency ($t(38) = 0.42$, $p = .67$) (Fig. 7).

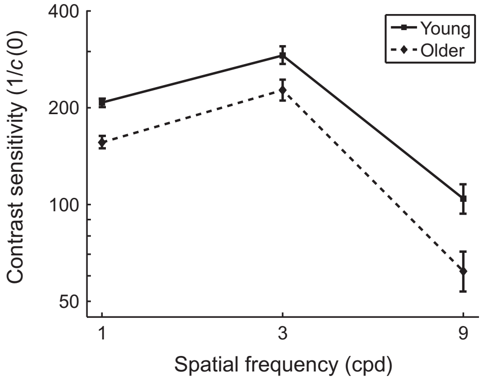

Fig. 4. Contrast sensitivity functions for the two age groups. Error bars represent the standard errors of the mean.

Fig. 6 represents the measured internal equivalent noise with local, static (left) and extended, dynamic (right) noise as a function of the spatial frequency. Again, the interpretations differed depending on whether local, static noise or extended, dynamic noise was used. With local, static noise, internal equivalent noise was not significantly affected at any spatial frequency ($t(38) = 1.53$, 0.37 and 1.36, $p = .13$, .71 and .18 for the low, medium and high spatial frequencies, respectively), and no simple main effect was observed ($F(1,38) = 1.76$, $p = .19$). With dynamic, extended noise, a significant effect was observed at the low spatial frequency ($t(38) = 3.59$, $p < .01$), but not at medium ($t(38) = 1.02$, $p = .32$) and high ($t(38) = 1.63$, $p = .11$) spatial frequencies (Fig. 7). Nonetheless, although a significant effect was observed only in one condition, no frequency × age interaction was observed ($F(2,76) = 1.33$, $p = .27$) and simple main effect of age ($F(1,38) = 5.76$, $p < .05$) was observed so we cannot exclude the hypothesis that internal equivalent noise was affected uniformly across all spatial frequencies.

Interestingly, opposite patterns of results were observed at the low spatial frequency between the two noise types (Figs. 6 and 7). With local, static noise, aging significantly affected the calculation efficiency, but not the internal equivalent noise. With extended, dynamic noise, aging significantly affected the internal equivalent noise, but not the calculation efficiency. These opposite patterns of results suggest that age-related effects on internal equivalent noise and calculation efficiencies varied depending on the noise type, which was statistically confirmed by a two-way ANOVA showing an age × noise-type interaction ($F(1,38) = 9.88$, $p < .01$). Conversely, no interaction was observed at the medium and high spatial frequencies ($F(1,38) = 0.67$ and 0.35, $p = .42$ and .56, respectively). Anyhow, the important finding was that the age-related effect depended on the noise type in at least one condition (low spatial frequency), which implies that the two noise types are not always equivalent.

4. Discussion

The goal of the current study was to evaluate whether age-related contrast sensitivity losses are due to increased internal noise or lower calculation efficiencies. If we were to apply the external noise paradigm using local, static noise and assumed the same processing strategy operates in absence and presence of static, local noise, then the age-related contrast sensitivity loss would be primarily attributed to a lower calculation efficiency at all spatial frequencies. However, such external noise was found to affect the processing strategy (Allard & Cavanagh, 2011). Using extended, dynamic noise, which has not been found to affect the processing strategy (Allard & Cavanagh, 2011), age-related contrast sensitivity losses would be attributed to higher internal equivalent noise at the low spatial frequency and a lower calculation efficiency at medium and high spatial frequencies (probably combined with higher internal equivalent noise).

4.1. Calculation efficiency

The results using extended, dynamic noise at the low spatial frequency are inconsistent with the results using local, static noise observed here and elsewhere (Bennett, Sekuler, & Ozin, 1999;

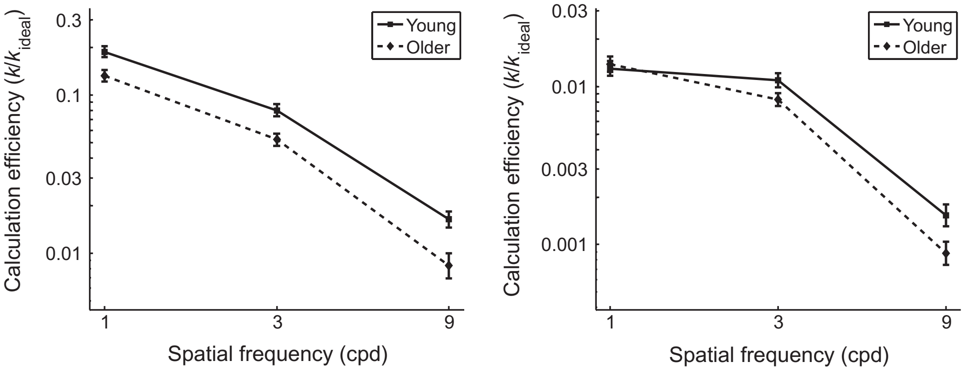

Fig. 5. Calculation efficiency as a function of the spatial frequency when using local, static noise (left) and extended, dynamic noise (right). Note that to represent the calculation efficiency, it was necessary to calculate the ideal efficiency (k_{ideal}), which depends on the threshold criterion (70.7%), the fact that it was a 2-alternative forced-choice, the spatiotemporal window of the signal and the phase uncertainty. Detail of this calculation can be found elsewhere (e.g., Bennett, Sekuler, & Ozin, 1999). Error bars represent the standard errors of the mean.

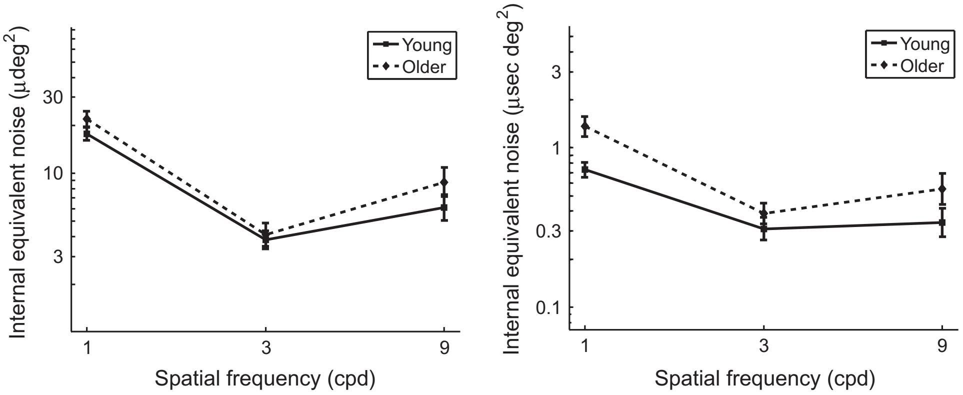

Fig. 6. Internal equivalent noise as a function of the spatial frequency when using local, static noise (left) and extended, dynamic noise (right). Consistent with previous studies, the internal equivalent noise is represented in noise spectral density units, which is proportional to the squared noise contrast (σ^2_{int}). Details on how to calculate the internal equivalent noise can be found elsewhere (e.g., Pelli, 1981). Error bars represent the standard errors of the mean.

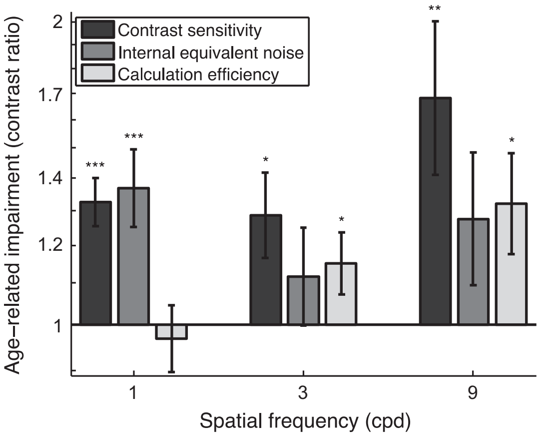

Fig. 7. Age-related impairments for contrast sensitivity (Fig. 4), internal equivalent noise (Fig. 6, right) and calculation efficiency (Fig. 5, right) when using extended, dynamic noise. The impairments are calculated as an age-related decrease in contrast sensitivity, increase in internal equivalent noise express in contrast units (σ_{int}) and decrease in calculation efficiency express in contrast units ($\sqrt{k}$). Note that in energy units (as in Figs. 5 and 6), the ratios are equal to the square of the contrast ratio. Results are presented in contrast ratio to be directly comparable with contrast sensitivity ratios so that the product of the internal equivalent noise and calculation efficiency deficits is equal to the contrast sensitivity deficit. Error bars represent the standard errors of the mean.

Pardhan, 2004; Speranza, Moraglia, & Schneider, 2001). With local, static noise, aging was found to have no significant impact on internal equivalent noise but affected the calculation efficiency, whereas the opposite pattern of results was observed with extended, dynamic noise. These diverging results are consistent with the hypothesis that different processing strategies operate in low and high local noise (Allard & Cavanagh, 2011). Thus, the contrast thresholds in high local, static noise would not depend on the calculation efficiency of the detection process as generally assumed, but on some properties of a discrimination or recognition process. This questions the validity of findings using local, static noise.

With extended, dynamic noise, no evidence that aging affected calculation efficiency at the low spatial frequency was found, that is, older observers were just as efficient as the youths to detect the target in noise. Consequently, the factors responsible for the age-related contrast sensitivity loss at the low spatial frequency affected the internal equivalent noise, not the calculation efficiency. In other words, the contrast sensitivity loss observed at the low spatial frequency cannot be explained by factors that would have also affected contrast thresholds in high noise, such as spatiotemporal summation or uncertainty.

At the medium and high spatial frequencies, different patterns of results were observed as aging was found to affect calculation efficiency. Thus, aging affects at least one factor of the calculation efficiency at medium and high spatial frequencies. It is unlikely that these effects were due to greater spatial or temporal uncertainty for the older observers since the stimulus' spatiotemporal window was large (>500 ms and >4 deg) and no effect was observed at the low spatial frequency with the same window. There is also no reason to think that there could be a frequency uncertainty effect at high spatial frequencies, but not at low spatial frequencies. Thus, it is unlikely that the selective age-related contrast sensitivity loss to medium and high spatial frequencies was due to some form of uncertainty. Conversely, the lower calculation efficiency could be due to a lower spatial or temporal integration.

Given that aging affects calculation efficiency at high but not at low spatial frequencies, an interesting hypothesis is that aging affects spatial integration. Although the spatial windows were the same in degrees of visual angle for low and high spatial frequencies, they differed in number of cycles. At the low spatial frequency, about 4 cycles were visible whereas about 12 and 36 were visible at the medium and high spatial frequencies, respectively. If older observers were able to integrate over more than 4 cycles but over fewer cycles than their youth, then this would result in a lower calculation efficiency when there are more cycles than what older observers can use. We are currently testing this hypothesis.

4.2. Internal equivalent noise

With extended, dynamic noise, a significant internal equivalent noise effect was found only at the low spatial frequency in which case it explained the entire age-related contrast sensitivity loss of 0.12 log. Nonetheless, although no significant effect was observed at the medium and high spatial frequencies, roughly half of the age-related contrast sensitivity loss was attributable to the internal equivalent noise (0.048 and 0.11 log, respectively) and the other half to the calculation efficiency (0.061 and 0.12 log, respectively) (Fig. 7). Thus, it is likely that the age-related contrast sensitivity losses at medium and high spatial frequencies are not entirely due to lower calculation efficiencies, but would also be due to an increase in internal equivalent noise, which happens not to be significant. Furthermore, note that no frequency × age interaction was observed for the internal equivalent noise and there was a main effect of age, which is compatible with an age-related internal equivalent noise increase that is equal across all the tested spatial frequencies. Thus, the current findings do not enable us to determine if aging effects on internal equivalent noise were due to a common factor to all spatial frequencies or different factors.

In her recent review, Owsley (2011) concluded that the age-related contrast sensitivity loss at high spatial frequencies was due to both optical and neural factors. With age groups similar to the current study, she concludes that about 0.1–0.2 log would be due to neural factors. This is compatible with the lower age-related calculation efficiency we observed at the high spatial frequency (0.12 log, Fig. 7). Given that optical factors should affect internal equivalent noise but not calculation efficiency (e.g., Pardhan, Gilchrist, & Beh, 1993) and that a substantial proportion of the age-related contrast sensitivity loss at high spatial frequencies is due to optical factors, this suggests that age-related increase in internal equivalent noise (0.11 log) was due to optical factors.

Although the higher internal equivalent noise at the high spatial frequency is likely due to optical factors, the origin (optical vs. neural) of the higher internal equivalent noise at the low spatial frequency is more difficult to determine. On one hand, common optical factor (e.g., reduced retinal illumination) could affect contrast sensitivity to all spatial frequencies. On the other hand, most optical factors would mainly affect high spatial frequencies and the higher internal equivalent noise at the low spatial frequency could be due to higher neural noise. Further investigation is required to determine the origin of the greater internal equivalent noise at low spatial frequencies.

4.3. Conclusion

The present study reassessed the origin (internal noise vs. calculation efficiency) of age-related contrast sensitivity losses using external noise that does not violate the noise-invariant processing assumption. We found that age-related contrast sensitivity losses were due to higher internal noise at low spatial frequencies and to lower calculation efficiencies at high spatial frequencies (probably combined with higher internal equivalent noise). We conclude that the efficiency of the detection mechanisms is affected with aging at high, but not at low spatial frequencies.

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