The Temporal Window of Visual Processing in Aging

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Purpose. Aging affects a variety of visual functions. In this study, we aim to quantitatively investigate the temporal characteristics of visual processing in aging.

Methods. Twelve younger (24.1 ± 1.6 years) and 12 older observers (58.4 ± 3.6 years) participated in the study. All participants had normal or corrected-to-normal vision. The contrast thresholds of the participants were measured using an orientation discrimination task with white external noise masks. The target-mask stimulus onset asynchronies were 16.7 ms, 33.4 ms, 50.0 ms, 83.4 ms, and ∞ (no external noise masks) in separate conditions. The signal stimulus was carefully chosen such that it was equally visible for the younger and older participants. An elaborated perceptual template model (ePTM) was fit to the data of each participant.

Results. Without masks, there was no difference in contrast thresholds between the younger and older groups ($P = 0.707$). With masks, contrast thresholds in the older group elevated more than those in the younger group, and the pattern of threshold elevation differed in the two groups. The ePTM fitted the data well, with the older observers having lower template gains than the younger observers ($P = 3.58 \times 10^{-6}$). A further analysis of the weight parameters of the temporal window revealed that the older observers had a flatter temporal window than the younger observers ($P = 0.025$).

Conclusions. Age-related temporal processing deficits were found in older observers with normal contrast sensitivity to the signal stimuli. The deficits were accounted for by the inferior temporal processing window of the visual system in aging.

Keywords: visual processing, external noise, contrast threshold, temporal window, efficiency, perceptual template model

Aging, even without any pathologic changes, affects a variety of visual functions,[1–3] including visual acuity,[4,5] contrast sensitivity,[6–8] orientation discrimination,[9] and reading speed.[10] The age-related visual deficits cannot be wholly accounted for by the inferior optical characteristics of the aged eye and could reflect additional deficits in central visual processing.[3,11–15] Using tasks with dynamic stimuli, such as local/global motion,[16–23] backward masking,[24–27] and rapid serial visual presentation (RSVP),[28–31] many studies have suggested that aging could impair temporal vision. In this study, we attempted to understand the mechanisms underlying the observed temporal deficits in aging by addressing two questions.

The first question is whether the observed temporal deficits in aging solely arise from age-related changes in temporal processing. Roudaia et al.[32] found that, whereas age-related deficits in apparent motion discrimination with small spatial displacements could be largely accounted for by reduction of visual acuity, deficits observed with medium and large spatial displacements could not be explained by differences in visual acuity. On the other hand, using a vernier task with shine-through masks,[33] Roinishvili et al.[27] and Pilz et al.[26] reported greatly increased threshold stimulus onset asynchronies (SOAs) in older compared to younger adults at the same performance level. In addition, with natural scene stimuli, Agnew and Pilz[25] reported that with a decrease of target-mask SOA, performance deteriorated with age, particularly for older adults over 70 years old. Interestingly, Roinishvili et al.,[27] Pilz et al.,[26] and Agnew and Pilz[25] all found that the observed performance deterioration in aging did not correlate with visual acuity. These results suggest that age-related temporal deficits might exist without visual acuity deficits. On the other hand, visual acuity is just one of many spatial vision measures that reflects the ability to resolve high-contrast stimuli and does not provide information about how well a participant perceives other spatial stimuli, such as low-contrast stimuli. In fact, Haegerstrom-Portnoy et al.[34] reported that visual acuity cannot predict other spatial vision measures on an individual basis despite high correlations between them across observers. To rule out the potential confound of spatial deficits, the properties of visual stimuli used in measuring temporal deficits must take age-related changes in spatial vision into account.

The second question is what aspects of visual processing in the temporal domain are affected by aging. In previous studies, age-related deficits were documented either by decreased accuracy in a range of target-mask SOA conditions[24,25] or by prolonged critical target-mask SOAs at certain performance levels.[26,27] Many studies in visual memory, integration masking, and temporal processing have suggested that there is a short period of time, termed *temporal window*, within which the visual system integrates dynamic visual inputs.[35–38] Although age-related performance change as a function of target-mask SOA has been reported in a number of studies,[24,25] it would be much more straightforward to directly characterize the temporal window at different ages.

Lu et al.[39] used white external noise masks that were symmetrically placed around the target stimuli in time and measured the contrast thresholds of the target in a range of different target-mask SOA conditions. By extending the original perceptual template model[40,41] with a temporally weighted perceptual template, Lu et al.[39] estimated the temporal profile of visual processing in different attention conditions. In this study, we adopted the paradigm and modeling framework introduced by Lu et al.[39] to investigate temporal processing deficits in aging. Although any temporally localized masks could reveal the masking effect as a function of target-mask SOA,[24] effects of white external noise mask have been well documented and easier to model.[40–43] In addition, the elaborated perceptual template model (ePTM) provides a computational framework for us to estimate the temporal processing window in aging.

To answer these two questions, we measured the contrast thresholds of younger and older observers in an orientation discrimination task with external noise masks in multiple target-mask SOA conditions.[39] The two-alternative forced choice (2AFC) orientation discrimination task with the Gabor stimuli oriented ±45° from vertical has been extensively used to measure the spatial contrast sensitivity function in previous studies.[44–46] Owsley et al.[47] reported that although the contrast sensitivity for stationary gratings in high spatial frequencies decreased with age, the contrast sensitivity in low spatial frequencies did not change through adulthood. So the spatial frequency of the signal stimuli was carefully chosen such that the younger and older groups had the same contrast thresholds to the (unmasked) signal stimuli. The ePTM[39] was fitted to the data to account for the performance difference between the younger and older observers. The temporal profile of the perceptual template was estimated based on the best-fitting model parameters and compared between the younger and older groups to isolate age-related changes in temporal processing.

Materials and Methods

Participants

Twelve graduate students (Y1–Y12, five male and seven female) from 20 to 26 years old (24.1 ± 1.6 years) at Wenzhou Medical University and twelve older observers (O1–O12, five male and seven female) from 55 to 66 years old (58.4 ± 3.6 years) from the local communities in Wenzhou, China, participated in the study. All participants have gone through detailed ophthalmologic and optometric examinations performed by the first and third authors. All observers had normal or corrected-to-normal vision (minimal angle resolvable ≤1.0 arcmin). The younger observers showed no sign of any eye disease. The old observers had no eye disease except some of them had some minimum cataract in one or two eyes. These eyes were graded as "cortical trace" according to the Lens Opacities Classification System II (LOCS II), which has seven cortical grades: 0, trace, 1, 2, 3, 4, and 5.[48] Typically, the presence of significant lens opacity is defined by a LOCS II score ≥2.[49,50] With normal visual acuity, these participants did not have clinically significant cataract and needed no intervention according to the Preferred Practice Pattern Guideline from the American Academy of Ophthalmology Preferred Practice Pattern Cataract/Anterior Segment Panel.[51] We decided to include the data from the older participants with some minor cataract.

All observers were naive to the purpose of the study and were free from diabetes, hypertension, mental diseases, and cognitive deficits (Mini-Mental State Examination = 28.7 ± 0.89). They wore the best optical corrections at the test distance during the experiment. Eye dominance was determined with the hole-in-card method for each participant. The study adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review board of human subject research of the Eye Hospital, Wenzhou Medical University. Written informed consent was obtained from each observer before the experiment.

Apparatus

The programs used in experiment were written in MATLAB (The MathWorks Corp., Natick, MA, USA) with Psychtoolbox.[52] The masking experiment was run on a HP ProDesk 680 G2 MT computer (Hewlett-Packard, Palo Alto, CA, USA). Stimuli were displayed on a gamma-corrected Sony Multiscan G520 CRT display (Multiscan G520; Sony Corp., Tokyo, Japan) with a mean luminance of 44.6 candela/m^2. The display had a spatial resolution of 800 × 600 pixels and a refresh rate of 120 Hz. Each pixel subtended 0.01 degrees at a viewing distance of 2.88 m. A chin/forehead rest was used to minimize head movement during the experiment. Observers viewed the stimuli monocularly with their best correction if any in a dark room. The eye not being tested was occluded by an opaque patch.

Stimuli

Based on the results from a pilot experiment, the center spatial frequency of the Gabors was set at 2 cycles per degree (cpd) to guarantee that the younger and older groups had equal contrast sensitivity to the signal stimuli in the experiment (as shown later in Results section). The Gabor stimuli, oriented ±45° from vertical, were rendered on a 300-pixel × 300-pixel grid. The wavelength of the Gabors was the same as the standard deviation of the Gaussian window.

The size of the external noise images was also 300 × 300 pixels. The check size of the noise was 10 × 10 pixels, which equals one-fifth of the wavelength of the signal stimuli. The Michelson contrast of each noise check of every external noise image was independently sampled from a Gaussian distribution with a mean of zero and a standard deviation of 0.33. Background luminance was added to all external noise images. All signal and external noise frames were centered at fixation.

The same temporal configurations in Lu et al.[39] were used. The stimulus in each trial consisted of a sequence of

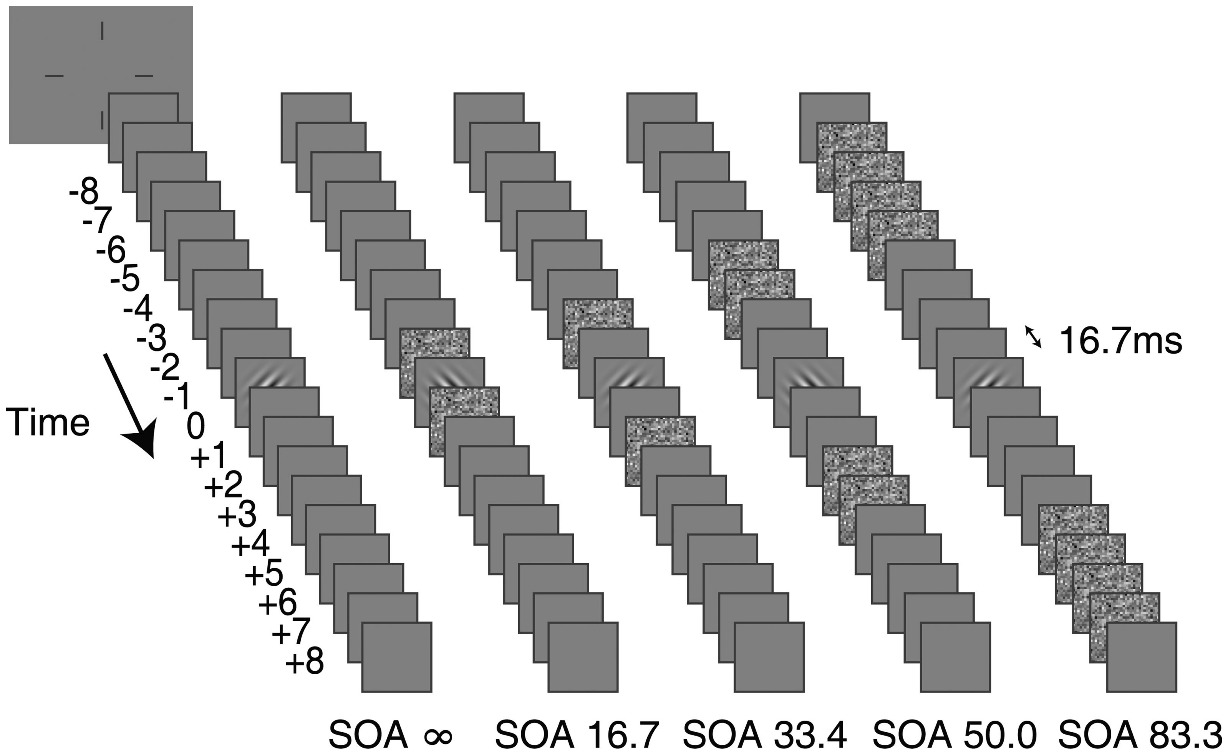

Figure 1. Temporal configurations of the external noise-masking experiment are shown. From *left* to *right*, the no-noise condition, marked as SOA ∞, and the four noise conditions with SOA 16.7 ms, SOA 33.4 ms, SOA 50 ms, and SOA 83.3 ms.

17 image frames, and each frame lasted two display refresh cycles (16.7 ms). The ninth frame was the Gabor stimulus. The noise frames were always symmetric around the signal frame. We denoted the position of the signal frame in the sequence as 0, the frame positions before the signal as -8 to -1, and those after the signal frame as 1 to 8. Five external noise configurations were used: no noise and external noise images occupied symmetric ±1, ±2, ±3, 4, and ±5, 6, 7, 8 positions, which in the rest of the article are noted as SOA ∞, SOA 16.7 ms, 33.4 ms, 50.0 ms, and 83.4 ms, respectively (Fig. 1). The remaining frames in the 17-frame sequence other than those of signal or external noise were filled with blank images.

Design

We limited the external noise masks used in the experiment within the "integration masking" conditions. This allowed us to use symmetrical temporal configurations of external noise around the target stimuli (see Discussion for detailed explanation).

The quick forced-choice method,[53] a Bayesian adaptive test for estimating sensory thresholds at predefined performance levels in forced-choice identification tasks, was used to measure the monocular contrast thresholds at three different performance levels (percentage correct = 65%, 75%, and 85%, respectively). The five masking configurations and three performance levels were mixed in random order with equal number of trials (50) in each experimental session. Each experimental session consisted of 750 trials and lasted about 40 minutes, with the two eyes of each observer tested in two separate sessions. The observers were given a practice session of about 100 trials before the experiment started.

Procedure

Each trial began with a brief tone signaling its onset and the presentation of a crosshair fixation (250 ms) in the center of the screen, followed by a blank screen (125 ms) with background luminance and then by the 17-frame ($16.7 \times 17 = 283.9$ ms) stimulus sequence and another blank frame that lasted until response. Observers were asked to indicate whether the Gabor stimulus was oriented to the left or to the right from vertical by pressing the left or right arrow key on the computer keyboard. Auditory feedback was provided after each correct response. A new trial started 500 ms after the response.

Analysis

For each observer, there was a total of 5 (external noise configuration) $\times$ 3 (performance) $\times$ 50 (trials). The raw response data were pooled across performance levels in each condition and fit with Weibull functions using a maximum likelihood procedure.[54] The contrast thresholds from the best-fitting models were used to analyze masking effects. Repeated ANOVA was used to analyze the effects of different factors as well as their interactions.

The Model

To characterize the temporal window of visual processing in the two groups, we fit the ePTM[39] to the behavioral data. The original PTM consists of an additive internal noise *Na*, a multiplicative noise *Nm*, the template gain of the perceptual template β, and a nonlinear transducer function γ.[40,41] The

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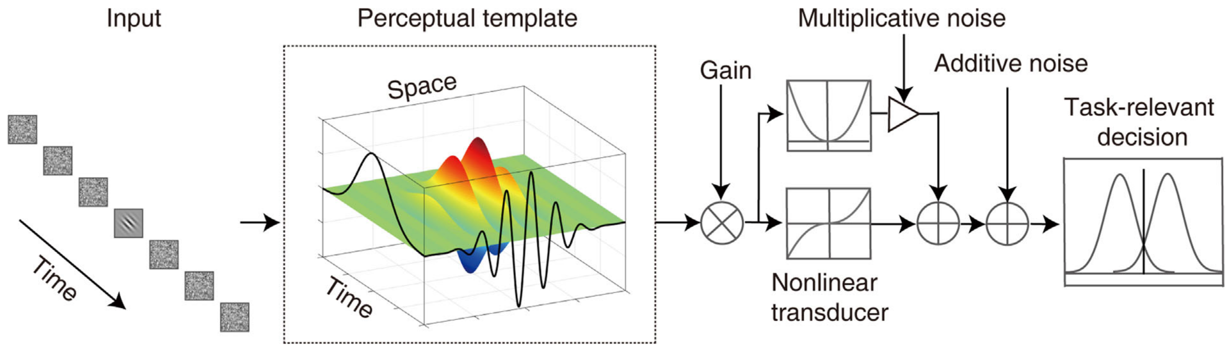

FIGURE 2. A diagram of the ePTM. It has five components: a perceptual template, a nonlinear transducer function, a multiplicative internal noise source, an additive internal noise source, and a decision process. The ePTM has a perceptual template with weights in the time domain. The masking effects at different target-mask SOA conditions can be used to infer the shape of the temporal window of visual processing.

performance of an observer can be written as

$$d' = \frac{(\beta c)^{\gamma}}{\sqrt{\left((\beta c)^{2\gamma} + N_{\text{ext}}{}^{2\gamma}\right)^2 N_m{}^2 + N_a{}^2}}, \tag{1}$$

where β represents the ability of the observer to extract the signal c from the external noise masks N_{ext}. In our experiment, the presentation of white external noise mask was systematically manipulated from −8 to 8 frames relative to the stimuli onset.

The ePTM has a perceptual template with weights in the time domain (Fig. 2). The masking effects at different target-mask SOA conditions can be used to infer the shape of the temporal window of visual processing. As the total gain of the perceptual template to external noise is normalized to 1.0 in the PTM,[40] we introduce the weights of the perceptual temporal window that satisfy the following constraint:

$$\sum_{t=-8}^{8} W_t{}^2 = 1. \tag{2a}$$

Recall that we have four different external noise configurations, corresponding to ±1, ±2, ±3, 4, and ±5, 6, 7, 8 image frame positions symmetrically distributed around the signal frame 0. That is to say, we can only obtain the average weight for the multiframe external noise conditions:

$$W_t = \begin{cases} W_{16.7}, \ if\ t = -1,\ 1, \\ W_{33.4}, \ if\ t = -2, 2, \\ W_{50.0}, \ if\ t = -4, -3,\ 3,\ 4, \\ W_{83.4}, \ if\ t = -8, -7, -6, -5,\ 5,\ 6, 7, 8. \end{cases} \tag{2b}$$

The parameters W_t of the temporal profile have been simplified to $W_{16.7}$, $W_{33.4}$, $W_{50.0}$, and $W_{83.4}$, which are to be optimized during the model-fitting process.

For external noise images each with variance σ^2, the total variance of external noise in a given temporal configuration is

$$N_{ext}{}^2 = \sum_{t=-8}^{8} (W_t \sigma_t)^2., \tag{3}$$

where $\sigma_t = \sigma$, when the noise frame presents and $\sigma_t = 0$ when the blank frame presents (Fig. 1).

Substitute equation 3 into equation 1, we have

$$d' = \frac{(\beta c)^{\gamma}}{\sqrt{\left((\beta c)^{2\gamma} + \left(\sum_{t=-8}^{8} (W_t \sigma_t)^2\right)^{\gamma}\right) Nm^2 + Na^2}}. \tag{4}$$

Then, the percent correct psychometric function of the observer can be derived from the d' psychometric function[55]:

$$P\ (c) = \int_{-\infty}^{+\infty} \phi\left(x - d'\left(c, f\right)\right) \Phi^{m-1}(x)\, dx\ , \tag{5}$$

where $m = 2$ for our orientation discrimination task, and $\varphi()$ and $\Phi()$ are the probability density and cumulative probability density functions of a standard normal distribution. The ePTM had seven free parameters: Na, Nm, β, γ, $W_{16.7}$, $W_{33.4}$, and $W_{50.0}$. Under the constraint in equation 2, we can calculate $W_{83.4}$ from the other three weights. The model was used to account for raw response data in each trial.

RESULTS

Masking Effects in Aging

We examined how external noise masks at different SOAs affected the contrast threshold of the orientation discrimination task. The contrast threshold was derived from the best-fitting Weibull psychometric function in each SOA condition. A repeated-measures ANOVA with factors of eye dominance, SOA, and age was carried out. There were significant effects of age ($F(1, 22) = 19.96$, $P = 1.93 \times 10^{-4}$), SOA ($F(4, 88) = 178.76$, $P = 2.254 \times 10^{-28}$), and age × SOA interaction ($F(4, 88) = 3.89$, $P = 0.006$). We found no significant effect of eye dominance ($F(1, 22) = 0.014$, $P = 0.909$), interaction between eye dominance and age ($F(1, 22) = 0.043$, $P = 0.839$), interaction between eye dominance and SOA ($F(4, 88) = 0.073$, $P = 0.99$), or interaction between the three factors ($F(4, 88) = 0.707$, $P = 0.589$). Given that there was no significant difference between the thresholds from the two eyes and the high correlation between thresholds in the two eyes ($r = 0.933$, $P = 4.63 \times 10^{-54}$), we used the averaged contrast thresholds from the two eyes in the following analysis.

The contrast threshold was plotted as a function of SOA for the younger and older groups (Fig. 3a). The thresholds in the older group were significantly greater than those in the younger group at SOA 16.7, 33.4, 50.0, and 83.4 ms (two-

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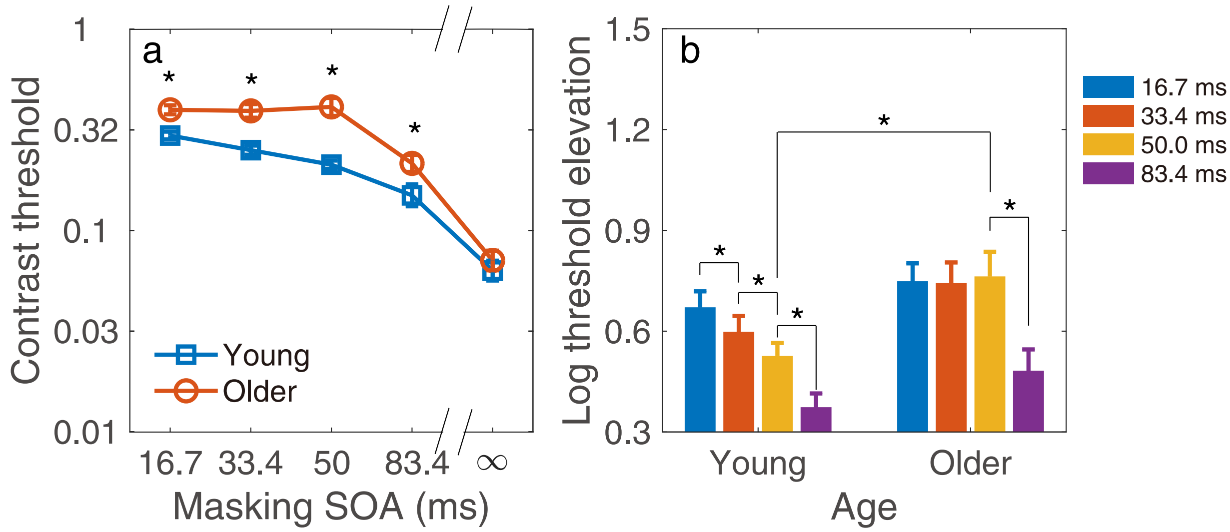

Figure 3. (**a**) Contrast threshold as a function of SOA is shown for the younger and older groups. The condition without external noise masking is denoted as SOA ∞ for consistency. *Blue*: younger group. *Red*: older group. (**b**) Threshold elevations in the younger and older groups. *Different colors* represent different SOAs. *Error bar*: ±1 standard error. *Asterisks*: statistical significance.

sample t-test, all Ps < 0.05). In contrast, there was no significant threshold difference at SOA ∞ between the two groups (two-sample t-test, $t(22) = 0.725$, $P = 0.476$), suggesting that spatial processing of the signal stimuli was equated in the two groups.

As evident by Figure 3 and by the significant age × SOA interaction, the two groups exhibited distinct patterns of temporal masking. To better demonstrate the difference in the temporal dynamics of masking, threshold elevations (log threshold ratio between masking conditions and the no-masking condition) are plotted in Figure 3b. Overall, the mean threshold elevation was marginally greater in the older group than in the younger group (0.684 ± 0.206 vs. 0.542 ± 0.130, $F(1,22) = 4.09$, $P = 0.056$). Again, there was a significant interaction between age and SOA ($F(3, 66) = 3.69$, $P = 0.016$), suggesting that threshold elevated differently with SOA in the two groups. For the younger group, as the SOA increased, threshold elevation decreased. The differences in threshold elevation between two adjacent SOA conditions were significant (paired t-test, Bonferroni corrected, all Ps < 0.05). In contrast, threshold elevation in the older group was almost constant until SOA reached 50.0 ms (paired t-test, Bonferroni corrected, all Ps > 0.05) and then decreased at SOA 83.4 ms (paired t-test, $t(11) = 5.42$, Bonferroni corrected, $P = 1.26 \times 10^{-3}$). This result indicated that the older observers were more severely affected by external noise masks than the younger observers. Furthermore, the masking effect had a wider temporal extent for the older observers than the younger observers.

Model Fitting

We fitted the ePTM (equation 5) to the trial-by-trial response data from the two eyes to derive the parameters of the model for each participant using a maximum likelihood procedure.[54] A χ^2 test was used to determine the goodness of fit.[54] A P value >0.05 means the model was statistically equivalent to the null hypothesis (i.e., a model of which parameters are the trial responses themselves), thus indicating a good fit. The goodness of fit for each participant is listed in Supplementary Table S1.

To better illustrate the goodness of fit of the model, the raw psychometric function of each masking condition and the model prediction for two representative observers (Y5 and O5) are shown in Supplementary Figure S1. The 300 trials in each masking condition were binned by dividing the log stimuli contrast range into six equal parts. The raw psychometric function was calculated as the percentage correct in the six bins in each masking condition.[56] Please note the binned psychometric functions are shown purely for illustration purposes. The actual data being fitted were trial-by-trial responses.

The ePTM provided good fits to the trial-by-trial response data for all participants (Supplementary Table S1). The additive internal noise, multiplicative noise, template gain, and the exponent of the nonlinear transducer for younger and older groups are shown in Figure 4a. There was no significant difference of internal additive noise, multiplicative noise, and nonlinear transducer function between the two groups (two-sample t-test, all Ps > 0.05). The template gain was significantly lower in the older group than in the younger group (0.563 ± 0.095 vs. 0.818 ± 0.108, two-sample t-test, $t(22) = 6.13$, $P = 3.58 \times 10^{-6}$).

Age-Related Change in Temporal Window

The temporal profiles W_t of the perceptual template from the best-fitting models for the two groups are plotted against SOA of each external noise conditions in Figure 4b. The unit of abscissa has been converted from frame into actual time (ms). As SOA increases, the weight decreases ($F(3, 66) = 312.8$, $P = 6.07 \times 10^{-39}$). There was a significant interaction between SOA and age ($F(3, 66) = 5.96$, $P = 0.001$). The temporal weight at SOA 16.7 ms was significantly lower in the older group than in the younger group ($t(22) = 2.85$, $P = 0.009$). The temporal weight at SOA 50.0 ms was higher in the older group than in the younger group ($t(22) = 4.01$, $P = 5.85 \times 10^{-4}$). There was no significant weight difference at SOA 33.4 and 83.4 ms between the two groups

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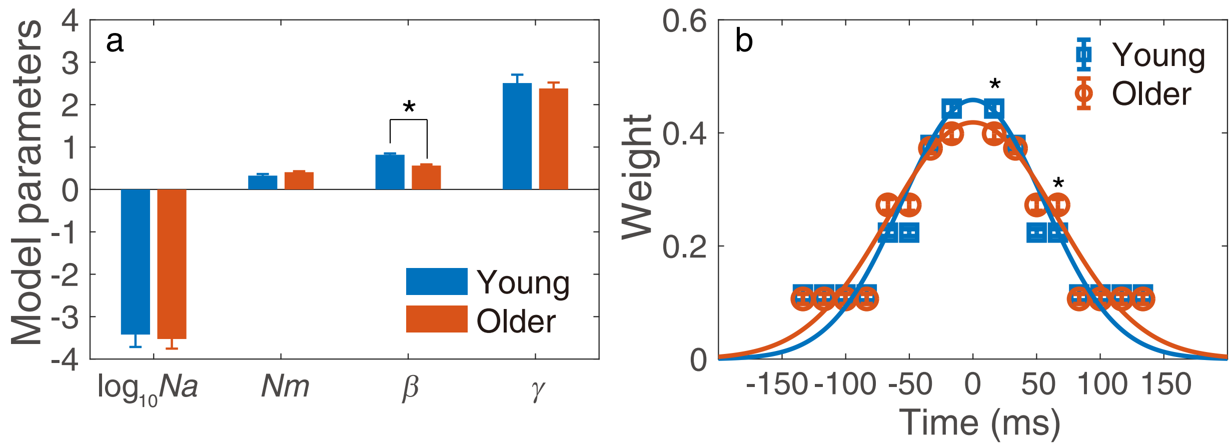

Figure 4. The average parameters of the best-fitting ePTM for two groups. (**a**) Additive noise *Na* in log10 unit, multiplicative noise, *Nm*, template gain β, and nonlinearity γ. (**b**) Derived temporal processing window ($W_{16.7}$, $W_{33.4}$, $W_{50.0}$, and $W_{83.4}$) of the two groups. *Blue*: Younger group. *Red*: Older group. *Error bar*: ±1 standard error. *Asterisks*: statistical significance. The continuous curves are best-fitting Gaussians.

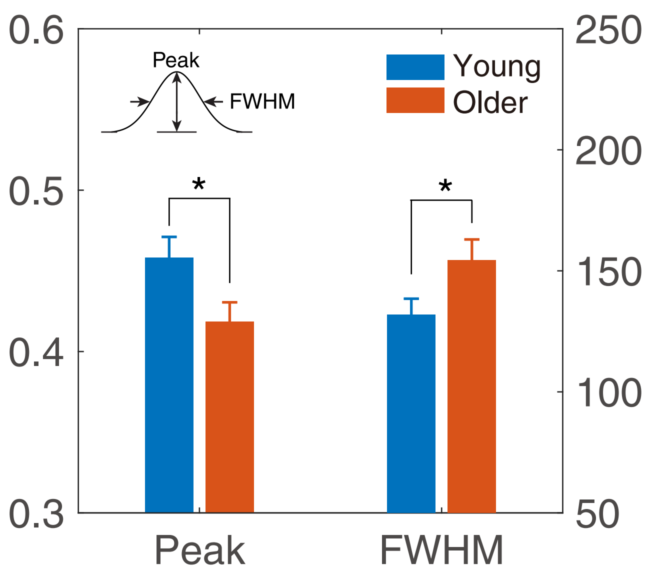

Figure 5. The peak and FWHM of the temporal window for the two groups. *Blue*: Younger group. *Red*: Older group. *Error bar*: ±1 standard error. *Asterisks*: statistical significance.

($Ps > 0.05$). It is worth noting that the reduced weight at SOA 16.7 ms does not contradict the increased contrast threshold for the older observers in the SOA condition (Figure 3a), because contrast thresholds are jointly determined by the signal gain β and weights W_t (equation 4). This is also why the older participants had a similar weight at SOA 33.4 ms to the younger participants yet higher threshold (Figure 3a).

To quantify the temporal profiles, a Gaussian function, $g(t) = peak \cdot \exp(-(\frac{t^2}{2\sigma^2}))$, was fit to the temporal window using the method of least squares. The contribution of each data point (W_i) to the sum of the residuals was adjusted to make sure that the data derived in each external noise condition contributed equally to the entire fitting. The peak amplitude and full width at half maximum (FWHM), computed as $2\sqrt{2\ln(2)}\sigma$, were derived for each observer (Fig. 5). The peak amplitude of the older observers was significantly lower than that of the younger observers (0.419 ± 0.041 vs. 0.458 ± 0.044, one-tailed, $t(22) = 2.27$, $P = 0.017$). The FWHM in the older group was significantly greater than that in the younger group (154.4 ± 29.8 ms vs. 131.8 ± 23.0 ms, one-tailed, $t(22) = 2.07$, $P = 0.025$). The results showed that the older observer had a flattened temporal window.

Discussion

In this study, we carefully designed the signal stimuli, such that there was no contrast threshold difference for the unmasked signal stimuli between the younger and older groups, and measured the contrast threshold in the orientation discrimination task under a variety of SOA conditions for all observers. We found that the contrast thresholds in the older group were almost the same as those in the younger group without masking. With external noise masking, the contrast thresholds were elevated more in the older group than those in the younger group in short SOA conditions, and the masking effect exhibited different temporal patterns in the younger and older groups. The ePTM was fit to the response data of all observers to further investigate the different masking effects in the temporal domain. No significant difference was found in terms of additive noise, multiplicative noise, or the nonlinearity of the best-fitting models between the younger and older groups. There was, however, a significant difference in the template gains between the two groups. A further analysis of the weight parameters of the temporal window revealed that the older observers had a flatter temporal window than the younger observers (FWHM: 154.4 ± 29.8 ms vs. 131.8 ± 23.0 ms). We conclude that the distinct patterns of temporal masking in the older group were due to deficits in temporal processing (i.e., the flattened temporal processing window). Most important, this temporal deficit can be observed in older observers with normal contrast sensitivity to the signal stimuli.

Consistent with previous masking studies,[24–27] we observed that older observers exhibited poorer performance relative to the younger observers under masking conditions when external noise masks were presented close to the signal in time. We carefully chose the stimuli so that the older and younger groups had essentially the same contrast threshold to the signal stimuli in the no-mask condition, and therefore the performance deterioration in aging was not caused by poorer spatial processing of the signal stimuli, consistent with Roinishvili et al.,[27] Pilz et al.,[26] and Agnew and Pilz,[25] who found that age-related temporal processing deficits were uncorrelated with visual acuity. Taken together, the results allowed us to conclude that the performance deficits under external noise masking were due to temporal processing deficits in aging.

Andersen and Ni[23] investigated the performance of younger and older observers in identifying two-dimensional shapes based on kinetic occlusion on a random dot texture background. They concluded that age-related changes in recovering two-dimensional shapes from kinetic occlusion were the result of spatial but not temporal integration. Arena et al.[22] measured the coherence threshold of global motion as a function of dot speed and spatial displacement in participants aged 20 to 70 years. Their result also indicated that the impaired performance in global motion perception of older adults was largely due to spatial integration. On the surface, our result may be inconsistent with these findings. However, our conclusions differ because we evaluated a different aspect of spatiotemporal processing. Whereas our study focused on temporal integration of dynamic visual inputs at the same spatial location, the aforementioned studies emphasized information integration across both space and time.

The ePTM analysis showed that the internal noise did not change with age while the template gain decreased in the older group. In fact, at a low spatial frequency (2 cpd), many studies[57–59] found that older observers had lower calculation efficiencies but similar internal equivalent noise, suggesting that aging affected the efficiency of the detection mechanism that extracts signal from noise. Li et al.[60] showed that Vernier acuity was reduced with increasing age, and the reduction in Vernier acuity could be mainly attributed to a reduction in sampling efficiency, with no significant change in the level of internal position noise in the visual system. Our finding is consistent with these studies. However, at high spatial frequencies (6–10 cpd), some inconsistent results have been reported in the literature. Pardhan[57] found a significant age-related change in internal noise and no significant change in calculation efficiency, but Bennett et al.[60] and Pardhan et al.[61] found an opposite pattern of results: a significant change in calculation efficiency and no significant change in internal noise. It would be interesting to apply the paradigm in this study to the stimuli at higher spatial frequencies to see whether and how the internal noise and calculation efficiency change with spatial frequency.

With the ePTM, we found that older observers had a decreased template gain and a flattened temporal window (i.e., reduced temporal tuning). The flattened temporal window may reflect functional decline of the cortex. In animal research, neurons in the primary visual cortex of old monkeys exhibited reduced orientation and directional selectivities,[62,63] and much of the reduction may result from a degradation of gamma-aminobutyric acid (GABA)–mediated intracortical inhibition during senescence.[63] With RSVP, people have also found age-related changes in visual temporal processing.[28,29,64,65] For example, with the attention blink paradigm, Lahar et al.[29] found that older adults are less able than their younger participants to suppress the task-irrelevant information, suggesting age-related inhibitory deficits (Hasher & Zacks, 1988[75]). The inhibitory deficit in aging has been also supported by evidence from studies in negative priming[66,67] and Stroop effects.[68] It has been reported that there was a significant negative correlation between age and GABA level in the frontal and parietal regions.[69] It is possible that the flattened temporal window observed in this study is related to inhibitory deficits in aging.

Traditionally, visual masking has been studied with brief masks at various mask onsets that either precede or follow the onset of the target. It has been shown that effect of forward (mask proceeds target) masking is greater than that of backward (mask follows target) masking.[70–73] In some conditions, such as “integration masking” conditions with very strong masks, however, the shape of the masking function has been shown to be approximately symmetric around zero target-mask SOA.[39,71,74] In this study, we used external noise masks with the highest achievable root-mean-square contrast (0.33) of the display and presented them in close temporal proximity of the target (SOA <200 ms). Such external noise masks belong to the regime of “integration masking” because of the limited temporal resolution of the visual system.[38] We assumed that the masking function is approximately symmetric around zero target-mask SOA and used external noise masks that were temporally symmetrical around the target to reduce the number of experimental conditions. An added benefit of symmetric masks is that they prevent the observer from “off-channel looking,” that is, shifting the center of the temporal window to match the signal-to-noise ratio profile in the stimuli in each trial.[73,74] With that being said, it is possible that the assumption of a symmetric masking function does not hold in the older population. In fact, Atchley and Hoffman[24] measured the performance of younger and older observers in forward and backward masking and found that the performance of the older observers became more asymmetric around zero SOA than that of the younger observer. Future studies should investigate the shape of the masking function in aging with both forward and backward masks.

By applying masking paradigm and controlling spatial processing of the signal stimuli, we can successfully isolate temporal processing deficits in aging. The current work is just the beginning for many future studies. It would be very interesting to study how the temporal processing window changes over age and how its properties are related to daily visual functions. Answering these questions will require many more observers with diverse characteristics and might provide more insights on the mechanisms underlying age-related spatiotemporal deficits in vision.

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