Vision Research 51 (2011) 417–423

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Combining vernier acuity and visual backward masking as a sensitive test for visual temporal deficits in aging research

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ARTICLE INFO

Article history:
Received 29 July 2009
Received in revised form 10 December 2010
Available online 31 December 2010

Keywords:
Temporal processing
Gender differences
Shine-through effect
Backward masking
Aging
Vernier acuity

ABSTRACT

Performance in many everyday situations slows down when age increases. The causes of slowing down may be found on any stage of information processing. Here, we show that the combination of a vernier acuity task and the shine-through backward masking paradigm is a good paradigm to determine temporal processing deficits. The paradigm is relatively robust to optical blur and unlikely affected by motor dysfunctions. Strong masking deficits are found from an age of about 50 years on.

1. Introduction

Performance in many paradigms deteriorates when age increases. Whereas optical and cognitive declines are well investigated, less is known about perceptual deficits even though perceptual deficits may cause or appear as cognitive deficits (e.g. Faubert, 2002). In many paradigms, elderly show a slowing down of performance (e.g. Birren & Fisher, 1995; Kallus, Schmitt, & Beneton, 2005; Salthouse, 1996). The underlying deficits may occur on many stages of information processing. For example, slowed performance in visual tasks can be caused by deficiencies of the optical system of the eye, of the retina, in the early visual areas, on cognitive stages, and during response execution. Whereas reaction times can tell about the prolongation of processing in general, it is usually impossible to infer the stages of deficient processing. For this reason, other paradigms are often used based on form from motion processing (e.g. Andersen & Ni, 2008) form from temporal structure (Blake, Rizzo, & McEvoy, 2008), and motion processing in general (Bennett, Sekuler, & Sekuler, 2007; Billino, Bremmer, & Gegenfurtner, 2008; Pilz, Bennett, & Sekuler, 2010).

Other good tools are visual masking (e.g. Walsh, 1978) and inspection time (Nettelbeck & Rabbitt, 1992; Gregory, Nettelbeck, Howard, & Wilson, 2008). In both paradigms, a target precedes a masking stimulus which impedes performance on the target. Deterioration of performance is usually much more pronounced in the elderly than in younger adults, i.e. the stimulus-onset-asynchrony (SOA) between target and mask onset is much longer. Increased SOAs may be taken as a measure for prolonged processing in the elderly. Motor-responses are unlikely to affect the results in these paradigms because reactions are not speeded.

Age strongly affects the optics of the eye. For example, optical blur increases strongly from age 40 years on. To cope with optical deficits, we used a vernier acuity task, which is relatively resistant to optical blur (e.g. Lakshminarayanan & Enoch, 1995; Stigmar, 1971). A vernier consists of two abutting vertical bars which are offset either to the left or right (Fig. 1). The task of the observer is to indicate this offset direction. To determine temporal deficits, the vernier was followed by a masking grating. If this grating comprises 25 elements, the vernier *shines through* the grating. Performance is better than for a grating with five elements where the vernier does not shine through. The vernier is largely invisible, particularly, for short SOAs (Fig. 1A and B; Herzog & Koch, 2001). The different masking power of the gratings cannot be explained on a retinal level only because the 25 element grating has a higher energy than the five element grating (the five element grating is part of the 25 element grating). For retinal processing, higher energy masks should deteriorate performance more strongly than lower energy masks because a higher energy mask adds, for example,

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doi:10.1016/j.visres.2010.12.011

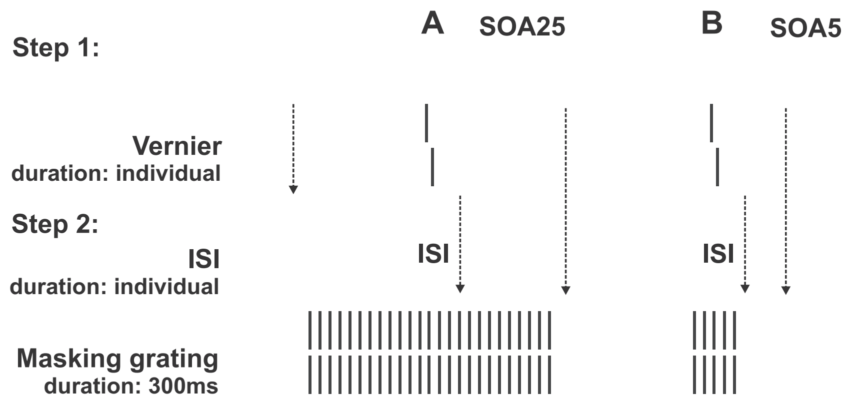

Fig. 1. Experimental set-up. First, for each observer individually, we determined the vernier duration (VD) for which the threshold of vernier offset discrimination was about 40″ or below. Subjects had to indicate whether the lower vernier segment was offset to the right (as shown here) or right in comparison to the upper segment. This individual vernier duration was used in the second step in which the vernier was followed by a masking grating comprising either 25 (A) or 5 (B) aligned verniers. In these conditions, we determined the ISI between vernier disappearance and grating onset to reach a performance level of 75% correct responses for a vernier with a constant offset of 1.19′. SOA = VD + ISI.

more noise. For this and other reasons, we expect non-retinal, visual processing to be involved in our masking paradigm. In a series of experiment, we showed that perceptual grouping is a key factor to explain the masking effects (Herzog & Fahle, 2002).

With this set-up, we show that elderly, on average, needed much longer SOAs between the vernier and the grating to reach a performance level comparable to younger observers. These temporal performance deficits are unlikely related to the very earliest stages of visual processing, i.e. the optics of the eye, and to the latest ones, i.e. motor-processing. We will argue that also memory and executive function deficits do not influence performance strongly. Hence, combining vernier acuity and visual masking is an interesting tool, for example, when optical blur can or should not be excluded.

2. Methods

2.1. General set-up

Stimuli were generated on a Pentium-based computer and displayed on a Siemens Fujitsu P796-1 monitor (31.0 cm (H) × 23.3 cm (V), 1024 × 768 resolution). Participants observed the stimuli binocularly from a distance of 3.5 m in a room illuminated dimly by a background light. A pixel comprised about 18 arc s at this distance. White stimuli were presented on a black background. Luminance of stimuli was approximately 100 cd/m^2. Background luminance was about 0 cd/m^2, hence, contrast was about 1.0. Refresh rate was 100 Hz.

In the masking experiments, a vertical vernier preceded a grating comprising either 25 or 5 elements (Fig. 1). A vertical vernier is composed of two bars that are slightly displaced in the horizontal direction either to the left or to the right. The length of a segment of the vernier, i.e. one bar, was 10 arc min. Segments were separated by a small gap of 1 arc min. Thus, altogether a vernier was about 21 arc min long.

On each trial, the vernier offset direction was chosen randomly either to the right or to the left. In a binary task, observers were asked to indicate this offset direction by pushing either one of two buttons. Errors were indicated by an auditory signal.

2.2. Observers

Ninety-one healthy subjects participated in the experiment (age range 15–78). Data of 25 of these 91 observers were also used in an experiment about schizophrenia research in which the 25 observers were part of a control group (age range of these observers: 20–52 years). The design of the study was approved by the local ethic committee and was performed in accordance with the Helsinki declaration. Before the experiment proper, the general purpose of the experiment was explained to each observer. Subjects were told that they could quit the experiment at any time they wished and signed informed consent. Only observers were included who had no signs of dementia and who were able to understand the task without any problems.

2.3. Procedure

The experiment was carried out in three subsequent steps.

2.3.1. Visual acuity

We determined visual acuity by means of the Freiburg visual acuity test (Bach, 1996). To participate in the following experiments, observers had to reach a value of 0.8 at least in one eye (equivalent to 20/25 Snellen fraction). Fourteen observers had to be excluded from the study because of reduced visual acuity.

2.3.2. Critical vernier duration (VD)

First, we presented unmasked verniers and determined offset discrimination thresholds, defined as the vernier offset size for which 75% correct responses are reached, using the adaptive staircase procedure PEST (Taylor & Creelman, 1967). For each observer, we aimed to determine the shortest VD for which the offset discrimination threshold was 40 arc s or below. In the first block, verniers were presented for 150 ms. In the following blocks, we reduced the VD when offset discrimination was below 40 arc s in the previous block while we increased it otherwise. Eighty trials were presented in each block.

To join the next step, the masking condition, a vernier duration shorter than 100 ms had to be reached. Eight subjects did not meet this criterion and were excluded at this step.

2.3.3. Backward masking

Sixty-nine observers (33 females and 36 males) passed the two previous tests. In the next condition, the vernier was followed by a blank screen (ISI; inter-stimulus interval) and a grating comprising either 25 or 5 aligned verniers, i.e. verniers without offset (Fig. 1). The aligned verniers had the same length as the vernier. For each observer, we used the individual critical vernier duration as determined in the last condition. We did not use vernier durations of 10 ms, corresponding to one flash on the screen only, because it turned out that performance in the masking conditions is often unreliable. For this reason, we used vernier durations of 20 ms and more depending on observer. The vernier offset size was set to 71 arc s. The horizontal distance between grating elements was about 3.33 arc min. The vernier and the central element of the grating appeared always in the middle of the screen. Gratings lasted for 300 ms.

To determine masking performance, we adaptively assessed the stimulus-onset-asynchrony (SOA) between target and mask. The SOA is defined as the difference between grating and vernier onset and is the sum of vernier duration and ISI (SOA = VD + ISI; Fig. 1). Whereas in the unmasked vernier conditions, the vernier duration was constant in one block and the vernier offset size was varied, in the masking conditions, both the vernier duration and the vernier offset size were constant while the SOA was varied from trial to trial. We determined the SOA for which a performance level of 75% correct responses was obtained with Probit and Maximum Likelihood analysis. The starting value of the SOA was 200 ms. Two thresholds for each grating were determined and their mean calculated. In many conditions, subjective visibility of the preceding vernier is completely abolished. If observers were unable to reach a threshold value of 400 ms or below, a value of 450 ms was recorded (for details see Herzog, Fahle, & Koch, 2001).

2.4. Statistical analysis

Descriptives include absolute frequencies for categorial variables, mean and standard deviation for numerical measurements. The relations between age, visual acuity, vernier duration, and SOA were analyzed using Spearman's rank correlation coefficients. In order to identify factors independently associated with age, multiple linear regression analyses with forward and backward model selection were performed, with age as the dependent variable and visual acuity, vernier duration, and SOA5 or SOA25 as the independent variables (an additional analysis was computed with SOA5 and SOA25 as the dependent variables). Mann–Whitney's U test was used for group comparisons concerning age of up to and above 50 years.

3. Results

3.1. Visual acuity

With increasing age, visual acuity declines ($r = -0.4$; $p < 0.001$; Fig. 2). Subjects older than 50 years display a significantly lower visual acuity than subjects younger than 50 years (1.5 vs. 1.7, $p = 0.009$; see Table 1).

3.2. Critical vernier duration

Subjects older than 50 years need significantly ($p < 0.0001$) longer vernier durations than subjects younger than 50 years (49.3 ms vs. 24.8 ms; Table 1; Fig. 3). Vernier durations are correlated with age ($r = 0.50$; $p < 0.001$; see Fig. 3).

3.3. Backward masking

Older observers need much longer vernier durations compared to younger participants (Fig. 3; Table 1). We used for each observer, the individual vernier duration to, at least partially, compensate for vernier acuity deficits of the elderly and to assure that observers are able to perform the task with the unmasked vernier.

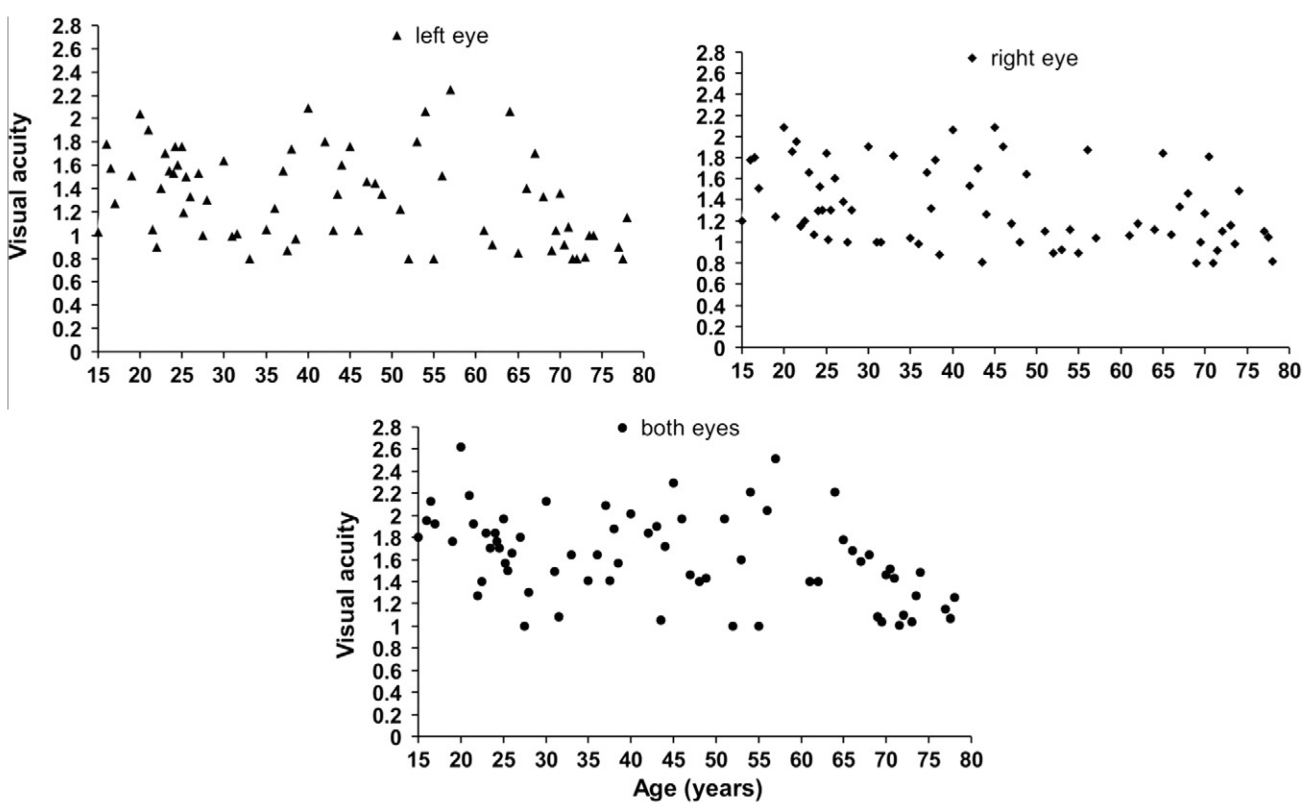

Fig. 2. Visual acuity, as determined by the Freiburg visual acuity test, declines with increasing age. Subjects with a visual acuity lower than 0.8 were excluded and their data is not shown here. In this and the following figures, each data point shows performance of one observer.

Table 1
Behavioral results (means and standard deviation) for all observers and for the two sub-samples of age below and above 50 years. *P*-values show the differences between the two groups (Mann–Whitney's U test).

	Total sample ($n = 69$)	Subjects <50 year ($n = 42$)	Subjects >50 year ($n = 27$)	p
Visual acuity	1.6 ± 0.4	1.7 ± 0.3	1.5 ± 0.4	0.009
Vernier duration	34.3 ± 24.0	24.8 ± 13.5	49.3 ± 28.9	<0.0001
SOA25	55.7 ± 56.2	33.5 ± 21.9	90.3 ± 73.9	<0.0001
SOA5	153.2 ± 103.9	101.9 ± 37.4	232.9 ± 123.2	<0.0001

In spite of this adjustment, there is still a strong deterioration of performance in backward masking with increasing age. This result holds for the mask with 25 elements (SOA25: $r = 0.60$; $p < 0.0001$) as well with five elements (SOA5: $r = 0.68$; $p < 0.0001$; see Fig. 4).

The performance of female and male participants did not differ. The correlations between age and SOA25 and SOA5, respectively, were significant for each gender separately; for females: SOA25 ($r = 0.585$, $p < 0.001$) and SOA5 ($r = 0.768$, $p < 0.001$) and for males: SOA25 ($r = 0.565$, $p < 0.001$) and SOA5 ($r = 0.588$, $p < 0.001$).

3.4. Regression analyses

All three main performance measures, i.e. VD, SOA25, and SOA5, were significantly and strongly correlated with each other (see Table 2; Spearman's r between 0.41 and 0.72). Visual acuity, however, showed no significant correlation with any of these measures (Table 2).

Vernier duration correlated strongly with the SOA25 and SOA5 (SOA25: $r = 0.41$; $p < 0.0001$; SOA5: $r = 0.64$; $p < 0.0001$). In order to determine if vernier duration and masking performance are associated with age independently, visual acuity adjusted multiple linear regression analyses were performed (Table 3). After backward and forward selection, SOA25 (standardized beta = 0.39, $p < 0.001$) and vernier duration (standardized beta = 0.27, $p = 0.013$) and visual acuity (standardized beta = –0.28, $p = 0.004$) remained independent predictors of the model (see Table 3). Variable selection with respect to SOA5 resulted in a model with SOA5 (standardized beta = 0.61, $p < 0.001$) and visual acuity (standardized beta = –0.23, $p = 0.015$) as independent predictors for age. SOA5 has a higher "predictive quality" for age than SOA25 (see standardized betas). SOA5 in combination with visual acuity fits the model better (adjusted $r^2 = 0.483$) than SOA25 in combination with both vernier duration and visual acuity (adjusted $r^2 = 0.435$).

We just like to mention that results do not change when SOA25 and SOA5 are taken as the dependent variables. Age (standardized beta and p-value =0.32 and <0.001, resp. 0.46 and <0.001) and vernier duration (standardized beta and p-value = 0.26 and 0.023 resp. 0.44 and <0.001) remain in the models after selection, with adjusted $r^2 = 0.365$ and 0.588, respectively, confirming the independent association of SOA with age (with SOA5 again showing the stronger relationship).

4. Discussion

In recent publications, we have shown that the shine-through masking paradigm is a very sensitive test for detecting differences in temporal processing between various populations. Schizophrenic patients (e.g. Herzog, Kopmann, & Brand, 2004; Schutze, Bongard, Marbach, Brand, & Herzog, 2007) and their non-affected relatives (Chkonia et al., 2010) showed strongly *elevated* SOAs whereas tennis players had *shorte*r SOAs compared to non-sportsmen and triathletes (Overney, Blanke, & Herzog, 2008).

Here, we have shown that the shine-through effect is also a suitable tool to determine deteriorated temporal processing in the elderly. Performance strongly decreased for observers from an age of about 50 years on (Fig. 4). For some elderly, an SOA25 of up to 317 ms (mean 90.3 ms) was found whereas the mean SOA25 for observers until the age of 50 years was only 33.5 ms.

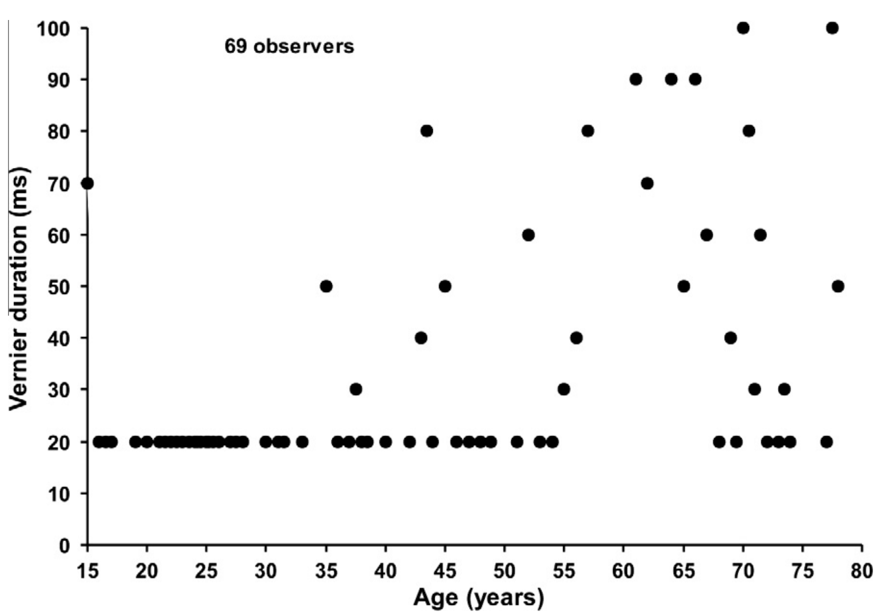

Fig. 3. Longer vernier durations are needed when age increases (vernier durations as used in the masking conditions are shown). Subjects with critical vernier durations longer than 100 ms did not join the following masking experiments and their data are not shown here.

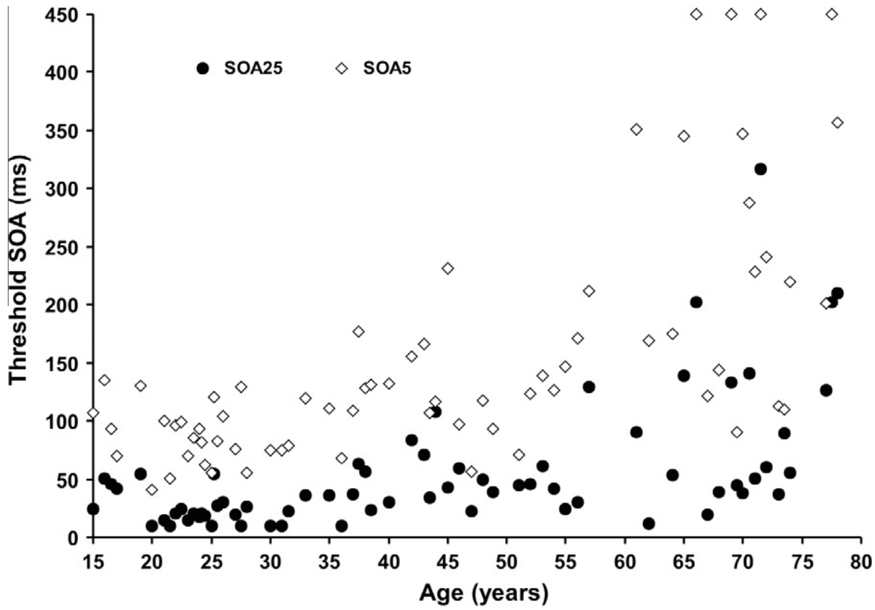

Fig. 4. Even though we provided substantially longer vernier durations for older observers, vernier discrimination strongly deteriorates when a masking grating follows. Thresholds of observers of age 70 and older ($n = 11$) are a factor of 5 higher than thresholds of subjects aged between 25 and 35 ($n = 12$). As usually, the masking effects of the five element grating are stronger than those of the 25 element grating indicating that energy is not the primary explanation for this kind of masking (see Herzog & Koch, 2001). SOAs of 10 ms indicate that the vernier and the grating were presented simultaneously for 10 ms. Sixty-nine observers participated.

Table 2
Correlation coefficients and p-values for age, visual acuity, vernier duration, SOA25, and SOA5.

	Age	Vis. acuity	VD	SOA25	SOA5
Age					
Vis. acuity					
r	−0.43				
p	<0.0001				
VD					
r	0.48	−0.20			
p	<0.0001	0.100			
SOA25					
r	0.60	−0.16	0.41		
p	<0.0001	0.180	<0.0001		
SOA5					
r	0.68	−0.24	0.64	0.72	
p	<0.0001	0.051	<0.0001	<0.0001	

While SOAs *on average* are strongly and significantly elevated, some elderly performed almost as good as the younger controls. This result opens the possibility for investigations why in some elderly temporal processing is strongly deteriorated but not in others.

We used a vernier discrimination task because vernier discrimination is largely resistant to optical blur and is, for this reason, proposed to be a gold standard in aging research. Vernier thresholds do not vary too strongly with age (e.g. Fahle & Daum, 1997; Lakshminarayanan & Enoch, 1995; however, see Garcia-Suarez, Barett, & Pacey, 2004; Li, Edwards, & Brown, 2000). Moreover, vernier acuity is also largely unaffected by retinal illuminance (e.g. Li et al., 2000; Waugh & Levi, 1993a; Waugh & Levi, 1993b). Accordingly, vernier acuity and visual acuity did not correlate strongly in our study (Table 2). However, we found an effect of age on vernier duration. Elderly of age 50 years and older needed vernier durations of 49.26 ms on average compared to 24.76 ms of observers with age below 50 years. This discrepancy with other studies is possible explained by the rather short vernier durations we used compared to these other studies (Garcia-Suarez et al., 2004; B. Barrett, personal communication, March 12, 2007; Lakshminarayanan & Enoch, 1995; Odom, Vasquez, Schwartz, & Linberg, 1989, where 250 ms were used). In the masking conditions, we provided individually adjusted vernier durations. With this manipulation, we assured that observers were able to perform vernier discrimination when no mask was provided and compensated, at least partly, for retinal illuminance differences and potential reductions in contrast sensitivity affecting vernier discrimination (Bradley & Skottun, 1987; Wehrhahn & Westheimer, 1990; Waugh & Levi, 1993a; Waugh & Levi, 1993b) reduced contrast sensitivity in elderly, (Wang, 2001).

Despite this adjustment, there was still an obvious and very strong deterioration of performance when a masking grating followed the vernier. Whereas there is a correlation between vernier durations and SOAs, multi-linear regression analysis showed that

Table 3
Results of multiple linear regression analyses with respect to age after forward and backward model selection.

	SOA25				SOA5			
	Beta	95%-CI for beta	Standardized beta	p-Value	Beta	95%-CI for beta	Standardized beta	p-Value
Visual acuity	−14.03	−23.50 to −69.54	−0.28	0.004	−11.51	−20.69 to −62.86	−0.23	0.015
Vernier duration	0.22	0.05–0.39	0.27	0.013	–	–	–	–
SOA	0.14	0.06–0.21	0.39	<0.001	0.12	0.08–0.15	0.61	<0.001
Adjusted r^2 for model fit	0.435				0.483			

there is an independent effect when vernier duration is used as a co-variate (Table 3). Hence, there is stronger masking in the elderly compared to controls which cannot be explained by the prolonged vernier durations only.

The masking effects in the shine-through paradigm point to visual processing deficits which likely involve cortical deficits. In general, mask strength in the shine-through effect can only be explained by complex spatial processing which is assumed not to occur before the primary visual cortex (e.g. Herzog & Fahle, 2002). Notably, mask energy does not explain mask strength: The 25 element grating yields much better performance than the five element grating even though it is contained in the 25 element grating, i.e. each photoreceptor triggered by the five element grating is also triggered by the 25 element grating. For masking paradigms related to retinal processing, it is just the other way around: energy matters but not the spatial layout (Turvey, 1973). SOAs for the five element grating are 233 ms for the elderly on average. Some elderly observers are still influenced by this grating when presented with an SOAs of 400 ms, i.e. a blank screen for more than 300 ms (most young observers perceive two clearly visible events with such long SOAs). Hence, vernier processing cannot be completed beforehand. Therefore, our results show a strongly increased window of vulnerability to backward masking in the elderly, particularly, for the low energy five element grating – once more arguing against interpretations in terms of mask energy and purely retinal deficits. However, we do not claim that there are no processing deficits on the retinal level that influence performance.

As with most masking paradigm (Kline & Szafran, 1975), it is very unlikely that motor deficits contribute to the prolonged SOAs because we determined accuracy and reactions were not speeded. The paradigm was well understood because observers managed the task, for example, when SOAs were long or the vernier was not masked. Task and stimulus–response mapping were identical in the unmasked and masked conditions. Hence, the memory and executive functions needed to cope with the masking paradigm seem to be intact. However, deficient attention and top-down effects may be potential causes of prolonged SOAs.

Our study is in good agreement with the very few studies on masking and aging (review: Walsh, 1978). These studies showed consistently that masking performance increases with age. A longitudinal study showed that inspection time, i.e. a masking paradigm in which instead of ISI the target duration is varied (ISI is always 0 ms), is very likely a biomarker for cognitive decline (Gregory, Nettelbeck, Howard, & Wilson, 2008). However, parts of deteriorated performance in the masking and inspection times studies may be caused by optical deficits (Walsh, 1978) because letters (e.g. Walsh, 1976), letter like stimuli (Gregory et al., 2008), or digits (Kline & Szafran, 1975) were used as targets which may be strongly affected by blur compared to the vernier stimuli we used (see also Di Lollo, Arnett, and Kruk (1982), for dot stimuli). It should be mentioned that in these masking studies no adjustment of target duration was carried out which we believe is important to make sure that the target is clearly visible when unmasked. Our study outperforms the previous masking studies by strongly increased SOAs revealing a long lasting period of time in which stimulus processing is vulnerable to masking. It will be of primary interest to investigate what causes these long SOAs and why some elderly show almost non-affected performance. Deteriorated performance of elderly was also found in other perceptual paradigm such as motion discrimination (Bennett et al., 2007). Here, a strong and abrupt deterioration of performance occurred not before an age of 70 years on.

It was proposed that gender is a strong predictor for performance loss in aging stronger than age itself (Pakkenberg & Gundersen, 1997). This effect was suggested to be linked to the protecting effects of estrogens (e.g. Morrison & Hof, 1997). We did not find any obvious performance differences between female and male observers across the entire age range indicating that gender does not selectively influence temporal visual processing (Fig. 5). Possibly, visual masking involves neural circuits that are different from those subserving working memory where gender differences were found (e.g. Braver & Bongiolatti, 2002; Rypma & D'Esposito, 2000).

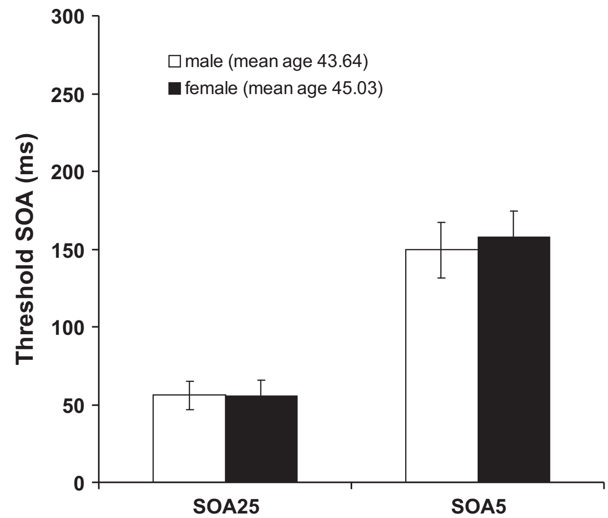

Fig. 5. Mean performance of female ($n = 33$) and male ($n = 36$) observers is roughly comparable. Error bars indicate the standard error of the mean.

One limitation of our study is its cross-sectional design. Longitudinal studies are needed to exactly determine the decline of performance with age. However, such a study is not easily conducted given the extended time range necessary to detect effects of aging (see Gregory et al., 2008). In our study, we investigated the time range of masking performance from 15 until 80 years. Our results suggest that measurements from year 50 on are a good starting point for a longitudinal study.

In summary, the strongly increased SOAs and the strong performance differences *within* the elderly population make the shine-through backward masking an interesting test when visual temporal processing is of interest and, for example, blur can or should not be excluded.

Acknowledgments

This work was supported by the Volkswagen Foundation project "Between Europe and the Orient – A Focus on Research and Higher Education in/on Central Asia and the Caucasus". We would like to thank Mike Martin, Ben Godde, Karin Pilz, and Anette Meistrowitz for useful hints regarding the aging literature.

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