

Blur Representation in the Amblyopic Visual System Using Natural and Synthetic Images

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PURPOSE. Amblyopia is diagnosed as a reduced acuity in an otherwise healthy eye, which indicates that the deficit is not happening in the eye, but in the brain. One suspected mechanism explaining these deficits is an elevated amount of intrinsic blur in the amblyopic visual system compared to healthy observers. This “internally produced blur” can be estimated by the “equivalent intrinsic blur method”, which measures blur discrimination thresholds while systematically increasing the external blur in the physical stimulus. Surprisingly, amblyopes do not exhibit elevated intrinsic blur when measured with an edge stimulus. Given the fundamental ways in which they differ, synthetic stimuli, such as edges, are likely to generate contrasting blur perception compared to natural stimuli, such as pictures. Because our visual system is presumably tuned to process natural stimuli, testing artificial stimuli only could result in performances that are not ecologically valid.

METHODS. We tested this hypothesis by measuring, for the first time, the perception of blur added to natural images in amblyopia and compared discrimination performance for natural images and synthetic edges in healthy and amblyopic groups.

RESULTS. Our results demonstrate that patients with amblyopia exhibit higher levels of intrinsic blur than control subjects when tested on natural images. This difference was not observed when using edges.

CONCLUSIONS. Our results suggest that intrinsic blur is elevated in the visual system representing vision from the amblyopic eye and that distinct statistics of images can generate different blur perception.

Keywords: amblyopia, blur perception, natural images

Amblyopia is a visual deficit that arises from a disruption in binocular visual experience, such as strabismus or anisometropia, during the critical period in childhood. In humans and in animal models, this visual deprivation leads to an ocular dominance shift of the cortical neurons in favor of the non-amblyopic eye, which itself leads to a decreased visual acuity in the deprived eye as well as a loss in contrast sensitivity at high spatial frequencies.^{1,2}

Both deficits in visual acuity and contrast sensitivity should lead amblyopes to be less sensitive to differences in blur compared to healthy observers. This internally produced blur (or neural blur) cannot be directly measured, but it can be estimated using the Equivalent Intrinsic Blur paradigm.^{3,4} That is, it can be estimated by modeling blur discrimination thresholds measured at various levels of external blur systematically added to the physical stimulus.⁵ Several studies have investigated blur perception in healthy and amblyopic populations with conflicting results. One report suggests that the amblyopic eye can be mimicked with higher level of blur and contrast,⁴ and, therefore, that its perceptual loss could be modeled with an increased level of intrinsic blur. However, other studies have reported no differences in internal blur^{3,6} and suggest that the amblyopic eye could be modeled by local spatial scrambling—that is,

by more distorted and perturbed spatial representations in the cortex.^{7–10}

Importantly, the bulk of previous studies have used synthetic images (e.g. a square-wave edge). To our knowledge, no study has used natural images to measure blur discrimination in amblyopia. It is well known that edges and natural images represent different types of information with differences that are nontrivial. Compared to synthetic images, natural images are statistically much richer, present greater variability across pixels in luminance and contrast, and can be more effective for driving visual cortex neurons.^{11–13} Because natural images are also functionally and behaviorally more relevant than synthetic stimuli, which are rarely encountered in the natural environment in which visual systems evolved, they can potentially reveal more complex underlying visual mechanisms. Conversely, testing only artificial stimuli could result in performance that is not ecologically valid due to the way our visual system is tuned.^{14–16}

We therefore aimed at filling this gap in the literature by measuring, for the first time, natural image blur perception in amblyopia and comparing those results to those obtained by synthetic images. Specifically, we sought to test two hypotheses—first, that vision through the amblyopic eye

TABLE. Clinical Characteristics of Amblyopic Subjects

Subject	Age/Sex	Type	Angle of Deviation	Eye	Refraction	Absolute VA Logmar	VA Difference in Log Mar	Stereo
AH	32/M	Mixed	10 Esotropia	FE AE	-1.00 +1.5	-0.3 0.4	0.7	400
CD	35/M	Strabismic	20 Exotropia	FE AE	Plano Plano	0 0.1	0.1	Nil
CF	54/F	Strabismic	9 Esotropia	FE AE	Plano Plano	0 0.15	0.15	100
CT	65/F	Strabismic	20 Exotropia	FE AE	+4.75 +5.00	0.2 1.4	1.2	Nil
DO	57/M	Strabismic	4 Esotropia	FE AE	+2.00 +2.00	-0.2 0.8	1	800
DT	38/M	Mixed	10 Esotropia	FE AE	Plano/-0.25 × 80 +4/-0.50 × 160	0 0.4	0.4	Nil
DV	28/M	Anisometropic	5 Esophoria	FE AE	+1.50 +3.50	0 0.1	0.1	60
GH	55/M	mixed	6 Exotropia	FE AE	-1.25/-0.5 × 30 +2.5/-1.5 × 75	0 0.4	0.4	50
JL	23/M	mixed	5 Exotropia	FE AE	-2.75 +1.75/-1.00 × 30	-0.3 0.2	0.5	400
JZ	22/M	Strabismic	5 Esotropia	FE AE	Plano Plano	-0.1 0.44	0.54	Nil
KS	27/M	Mixed	20 Esotropia	FE AE	+6/-1.75 × 120 Plano	-0.1 0.6	0.7	Nil
KW	23/F	Strabismic	5 Esotropia	FE AE	+1.75 /-1.00 × 170 +1.50 /-1.50 × 10	0 0.16	0.16	Nil
MPG	27/M	mixed	4 Esotropia	FE AE	+3.50 +5.25/2.25*30	0.1 0.7	0.6	Nil
SM	24/M	mixed	9 Esotropia	FE AE	-0.50 +2.50	-0.04 0.1	0.14	800

is affected by a higher level of intrinsic blur in the visual system compared to the fellow-fixing eye or healthy eyes. Second, that because of the statistical differences between natural and artificial stimuli, there will be a difference in the blur discrimination performance between natural images and edges for both amblyopic and healthy groups. We found evidence in support of the first hypothesis, but only when amblyopes were tested on natural images. This finding also supports our second hypothesis, that natural images and edges generate different blur perceptions. This study shows that assessing blur using simple artificial stimuli, such as an edge, could result in performances that are not ecologically valid. The results hint at the need for more generalizable stimuli and procedures in psychophysics.

METHODS

Observers

A test group of 14 amblyopes, 6 with strabismus only, 1 with anisometropia only, and 7 with both strabismus and anisometropia (mean age = 36.4 years old; SD = 11.93) were recruited for the study (see the Table). A control group of 14 observers (mean age = 37.3 years old; SD = 14.9; and 9 women and 5 men) with normal binocular vision and visual acuity were also recruited for the study. All amblyopic subjects were optically corrected for this experiment to ensure that the effects seen are due to amblyopia only. All experimental procedures adhered to the tenets of the Declaration of Helsinki. All research participants were provided with consent forms to make an informed and voluntary decision and were informed about possible consequences of the experiments.

Apparatus and Stimuli

Four natural colored images and one black-and-white edge were used as our testing stimuli (see Fig. 1). The natural images were acquired with a Nikon D90 camera, using the automatic mode and with RAW capture (12-bit color, uncompressed) and always with the SpyderCHECKR color standard for color correction. The captured images were color corrected by using reference color system of SpyderCHECKR and processed in Adobe Photoshop CS5.1 (64 bit) and Adobe Lightroom CC. The final images were cropped and stored as 16-bit TIFF files without compression to maintain their fidelity. Stimuli were blurred to different levels by convolving them with Gaussian kernel of various widths (see below), using the Image Processing Toolbox in MATLAB (R2016b.Ink, <https://www.mathworks.com/> developed by Cleve Moler and Edward B. Magrab). The size of the static blurred natural images and edge was 5.7 degrees × 6.7 degrees. All images were presented on a CRT monitor (LG Electronics Flatron 915 FT Plus) that was gamma corrected to ensure the linearity of the monitor luminance profile. Using a professional Nvidia Graphic Card (Quadro 2000), images were shown with 10 bits of depth (1024 levels in each color channel) on the analog monitor. The screen brightness was 30.75 cd/m² and the resolution was set to 1280 × 1024 with a refresh rate of 75 Hz. The viewing distance was fixed to 60 cm from the screen.

Procedure

Monocular image blur discrimination thresholds were measured in the fellow and amblyopic eyes of the amblyopic group and in the dominant and nondominant eyes of

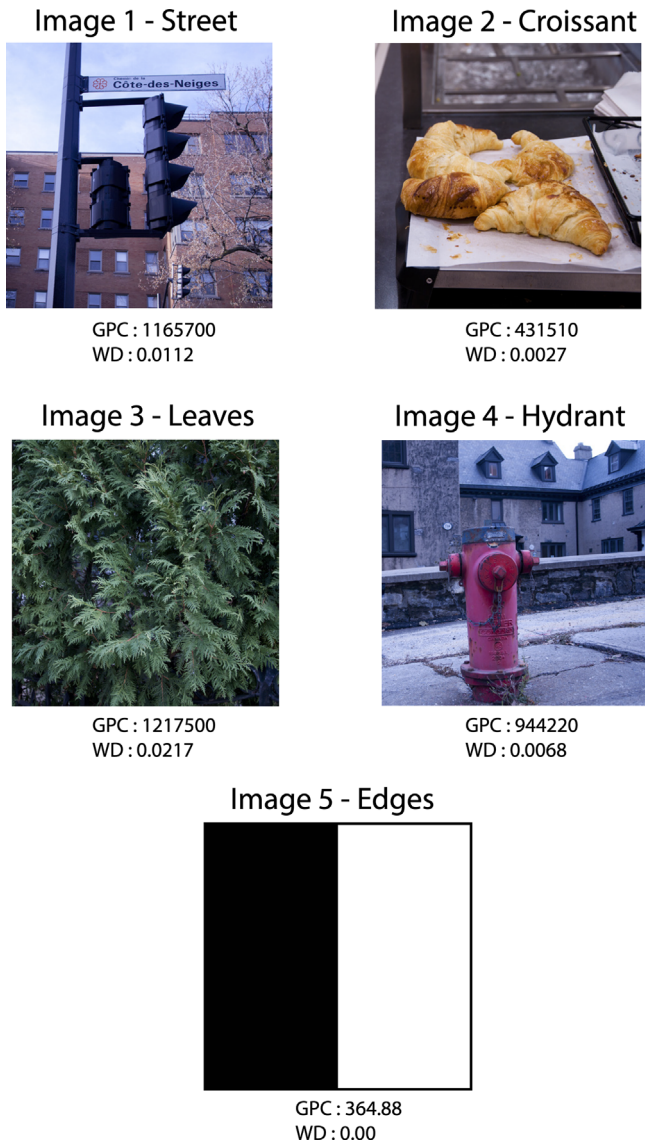


FIGURE 1. Images used for the blur discrimination task along with their respective sharpness index values (GPC : global phase coherence; WD : wavelength domain).

the control group. This was achieved by using an opaque eye patch on one eye at a time. Participants were tested on a two-alternative forced choice procedure. For the first session, one of the two eyes was patched so that monocular blur discrimination thresholds could be measured using a staircase approach. The choice of the first eye patched was done in a random manner (right or left) to remove possible confounding variables and counterbalance order effect. The stimuli were presented on each side of a fixation cross with an eccentricity of 1.9 degrees. The reference blur levels were expressed as standard deviation of a Gaussian and were fixed at 0, 0.23, 0.46, 0.94, 1.88, 3.75, 7.5, 15, or 30 arcmin. The standard deviation of the comparison blurred image was set to be always greater than that of the reference image by Δ blur. To prevent any strategy from the observer to use local contrast as a cue, we rotated the images at 90 degrees, 180 degrees, 270 degrees, or 360 degrees randomly from trial to trial (see Fig. 2). We also prevented

participants from using cues based on the pictures' external contour by using a Gaussian aperture that was set around the image (see schematic in Fig. 2).

The subject was seated in a dark room and instructed to fixate on a centrally presented cross. The participant then had to identify which of the two images (left or right) was the most blurred. Auditory feedback was given after each response (right or wrong, designated by a high or low tone). The first session consisted of five blocks, each testing one image (4 natural images and 1 edge) per block, and presented in a randomized order. Stimulus blur difference thresholds for each reference blur was determined using a 3-down-1-up staircase.

Once the first session was finished, participants were asked to remove the patch and wait for 1 hour and 15 minutes before doing the second session. This time was fixed to ensure the removal of any effects of patching.¹⁷ For the second session, the same procedure was repeated but this time with stimuli presented to the eye that had been previously patched. The same stimuli and the same number of blocks were used. The image order presentation was randomized across the blocks and the sessions.

Analysis

Data Collection and Pre-Processing. The subject's responses to each staircase step were used to estimate the threshold by fitting the responses with a Gumbel function using a maximum-likelihood routine implemented in Palamedes toolbox.¹⁸ For fitting the psychometric Gumbel function, we allowed the threshold and slope to vary and fixed the guessing rate at 0.5 and the lapse rate at 0.02. Prior to analysis, we validated the quality of the data to ensure that all staircases had converged, as this is a known problem with adaptive methods. For each subject, we ran 90 staircases, one for each reference blur and each eye and each image (i.e., 9 reference blurs \times 2 eyes \times 5 stimuli). In very few staircases, we did not have reliable convergence and therefore excluded those threshold estimates. This did not exclude the image or the eye or the subject—simply one threshold estimates from the nine needed to fit the dipper function for one eye in one subject. We were generally able to obtain good fits of the dipper function—out of a total of 2520 staircases ran across the 9 reference blurs, images, and eyes, only 58 failed, representing a failure rate of 2.3%.

Model Fitting. Blur discrimination performance follows a typical “dipper” function. That is, the discrimination thresholds first decreased with smaller reference blurs and then increase at larger reference blurs. The finding that subjects are generally most sensitive to incremental blur when it is added to slightly blurred images, but not to very sharp images, has been extensively reported in other experiments.^{3,6,19–24} We therefore fitted the data for each image and each eye with the Weber model, which has been widely used in other studies.^{20,22,25–27} We fitted a β and a ω parameter to the data for each eye and each image in both groups by using the following function²⁰:

$$a = -r + \sqrt{r^2 + (\omega^2 + 2\omega)(r^2 + \beta^2)} \quad 1$$

The β parameter represents the level of intrinsic blur in the visual system and the Weber ratio (ω) represents the sensitivity to blur differences. These parameters each have different effects on the dipper function: increasing the β parameter shifts the early part of the curve vertically and the

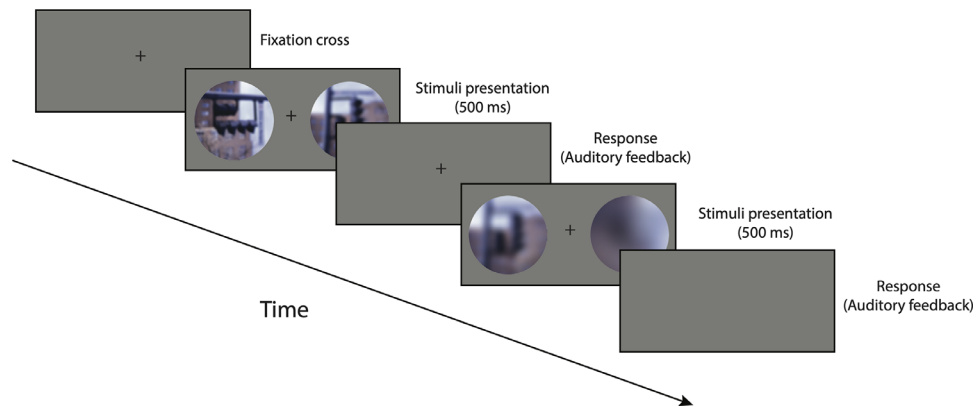


FIGURE 2. Schematic description of a two alternative forced choice task used in our study where the subject was asked to select the blurriest of the two images. Stimuli presentation lasted 500 ms followed by a grey screen.

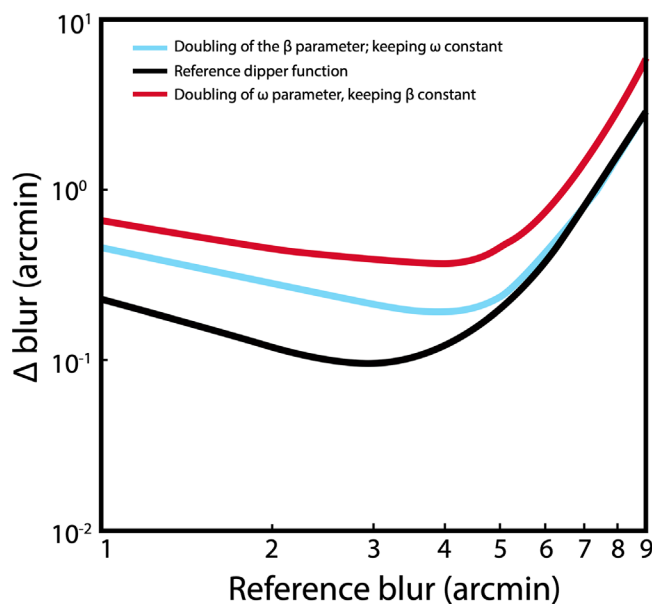


FIGURE 3. Predictions of the Weber model showing the effect of doubling the β parameter (intrinsic blur), while keeping the ω parameter (sensitivity) constant (blue) and the effect of doubling the ω parameter (sensitivity) while keeping the β parameter (intrinsic blur) constant (red).

dip horizontally, whereas increasing the ω parameter shifts the entire curve vertically (see Fig. 3).²⁸ The data were fitted to the model by using MatLab and by using the `fmincon` function to obtain estimates of β and ω parameters. These parameters were calculated for each eye and image in every participant and used for interocular comparison.

Inferential Statistics. We conducted a 2×2 mixed-design analysis of variance (ANOVA) using SPSS (IBM Corp.) with Eye (dominant/fellow vs. nondominant/amblyopic) as the within-subject factors, and patient group (healthy vs. amblyopic) as the between-group factor. The analysis was carried out separately for the β and ω parameters after outlier removal using Tukey's method,²⁹ which removed approximately 4% of parameter estimates across the 280 estimates made across the 5 images in 2 eyes of 28 subjects. The Greenhouse-Geisser correction was used to correct for variance nonuniformity.

We carried out planned comparisons using paired and independent sample *t*-tests, as well as exploratory post hoc analysis, corrected for false discovery rate using the Benjamini-Hochberg correction for multiple comparisons. Finally, we performed Spearman correlation between interocular logMAR acuity difference and the magnitude of dipper function parameter differences, to determine whether the differences were related to amblyopia or not.

RESULTS

Intrinsic Blur is Elevated in the Amblyopic Eye Only for Natural Images

All participants were able to adequately perform the task on both natural images and edges (Figs. 4A, 4B). When fitted to the Weber model, blur discrimination performance for both groups and both image types (natural and edges) followed a classic dipper function with thresholds first decreasing with smaller reference blurs and then increasing with larger reference blur.

Intrinsic blur levels were then compared for both groups by calculating interocular β parameter (reflecting intrinsic blur) from the fitted data for both natural images and edges in both groups. For the amblyopic group, a significant difference in β parameter was observed between the fellow eye and the amblyopic eye when using natural images, $t(10) = -2.632$, $P < 0.05$, with the amblyopic eye exhibiting higher intrinsic blur (Fig. 4C), whereas no differences were observed for edge stimuli. There was also a significant difference in ω parameter (reflecting sensitivity to blur differences) between the fellow and the amblyopic eye, $t(10) = -2.205$, $P < 0.05$ only when using natural images, suggesting that the amblyopic eye was less sensitive to blur differences in general across different levels of reference blur (see Fig. 4D). In the healthy group, a significant difference was also observed in the ω parameter using natural images whereby the nondominant eye was surprisingly more sensitive than the dominant eye, $t(8) = 2.464$, $P < 0.05$ (see Fig. 4D). However, no significant difference in the β parameter was found in the healthy group for both natural images and edges. This means that even if performance was generally better in the nondominant eye compared to the dominant eye when tested on natural images, the level of intrinsic blur in both eyes was equivalent in the healthy population.

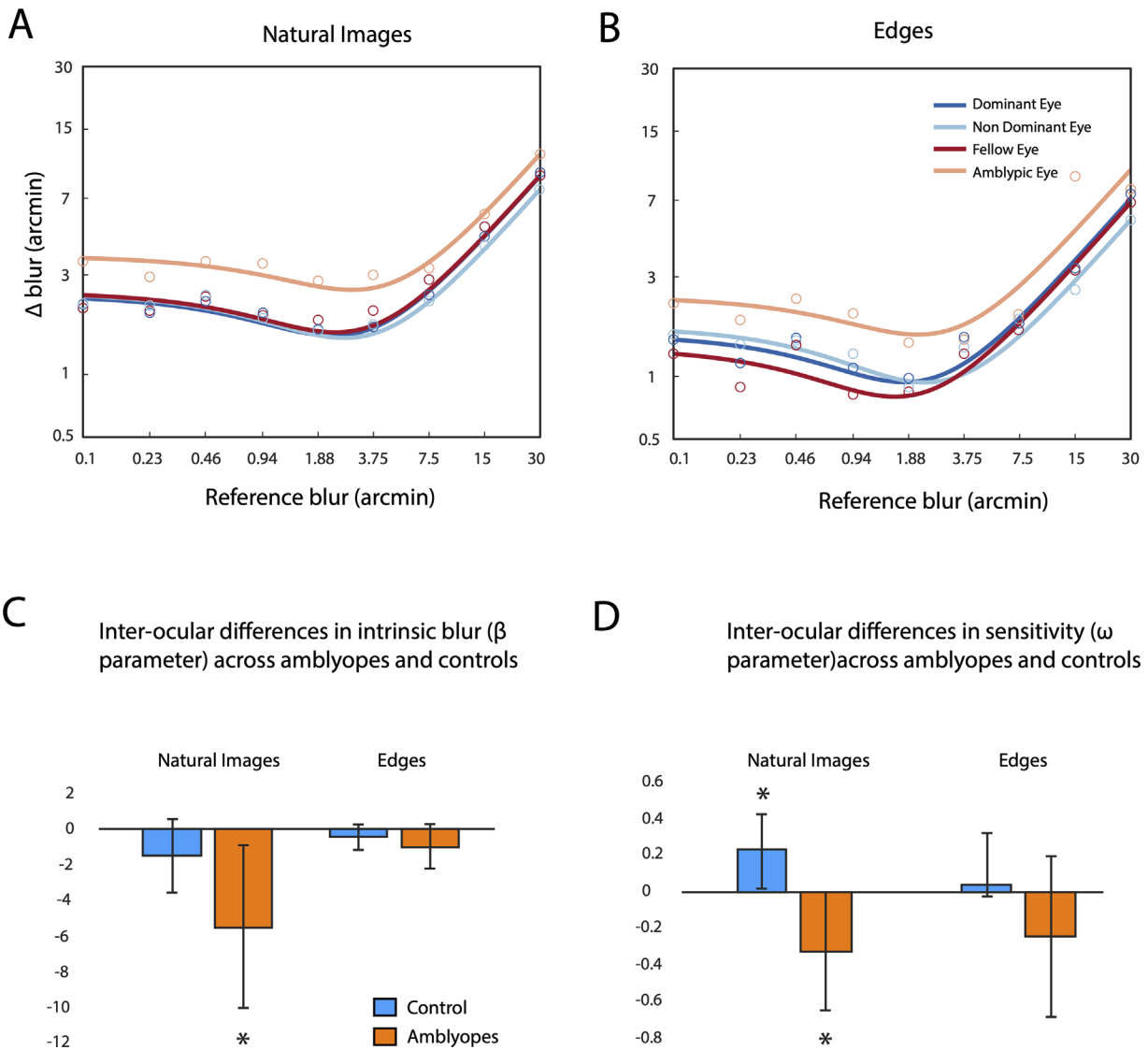


FIGURE 4. (A) Averaged monocular blur discrimination thresholds for all natural images for the amblyopic, fellow, dominant, and nondominant eye. (B) Averaged monocular blur discrimination thresholds for the edge stimulus for the amblyopic, fellow, dominant, and nondominant eye. (C) Mean interocular (within-subject) differences in β parameter (intrinsic blur) across groups (control and amblyopes) for all-natural images and edges. (D) Mean interocular differences in ω parameter (sensitivity) across groups (control and amblyopes) for all-natural images and edges.

We also compared β parameters between the amblyopic eye and the dominant eye of the healthy group using natural images, and found them to be significantly different, $t(23) = -2.386, P < 0.05$. This difference was also present when their ω parameters were compared, $t(23) = -1.9, P < 0.05$. The amblyopic and nondominant eye of the healthy group were also significantly different from each other both in terms of intrinsic blur, $t(20) = -1.703, P = 0.05$, and sensitivity, $t(20) = -2.298, P < 0.05$. The amblyopic eye therefore exhibited higher levels of intrinsic blur than the fellow eye, and both eyes of the healthy group when using natural images stimuli. This lends support to our first hypothesis, namely that intrinsic blur is elevated in the visual system representing vision from the amblyopic eye, compared to the fellow eye and the eyes of healthy subjects.

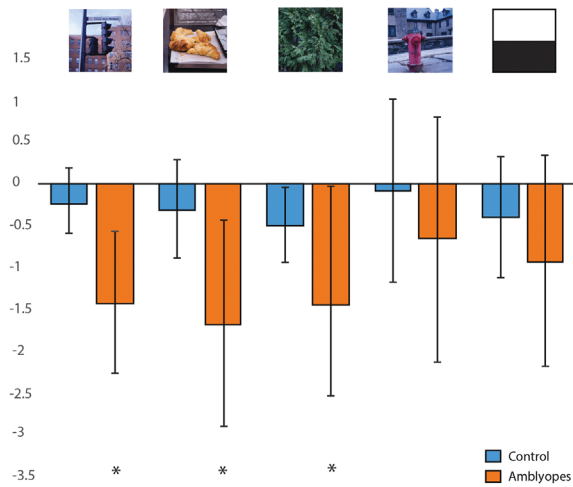
The synthetic edge stimulus resulted in patterns of blur discrimination that were comparable across eyes in both groups (see Fig. 4B) — we did not observe a significant

effect of eye difference in β (see Fig. 4C) and ω parameter (see Fig. 4D) in either group. This absence of an eye-specific effect lends support to our second hypothesis, namely that blur in natural images is perceived differently than synthetic stimuli.

Image-Specific Differences

In order to better understand the impact of image differences on blur perception and to eliminate the possible pooling effect in our previous analysis (only one synthetic edge stimuli was compared to the average response of 4 natural images), stimulus-specific differences were also studied using the Benjamini-Hochberg correction for multiple comparisons (Benjamini and Yekutieli, 2001) (Figs. 5 and 6). There was a significant difference in β parameter (intrinsic blur) between the fellow eye and the amblyopic eye

A Inter-ocular differences in intrinsic blur (β parameter) across amblyopes and controls for each stimuli



B Inter-ocular differences in sensitivity (ω parameter) across amblyopes and controls for each stimuli

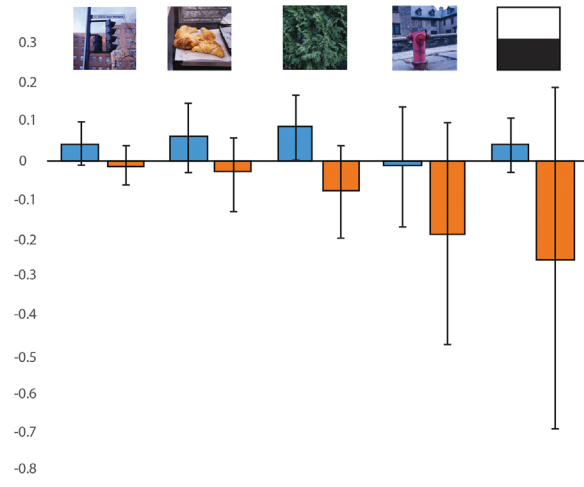


FIGURE 5. (A) Mean interocular differences in β (intrinsic blur) across groups (control and amblyopes) for each stimulus. (B) Mean interocular differences in ω (sensitivity) across groups (control and amblyopes) for each stimulus. Error bars reflect 95% confidence interval of the interocular difference.

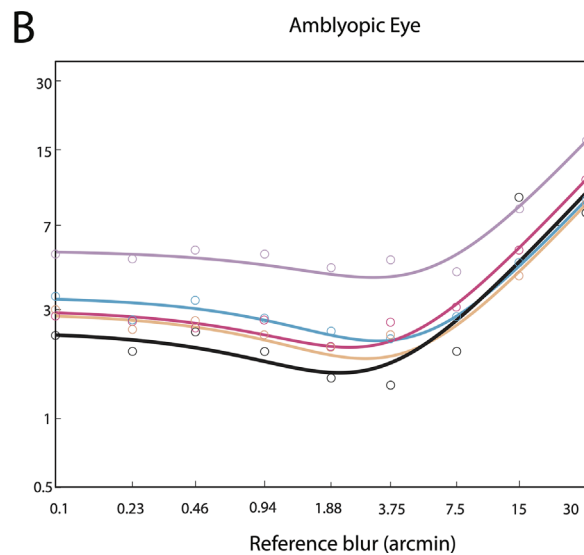
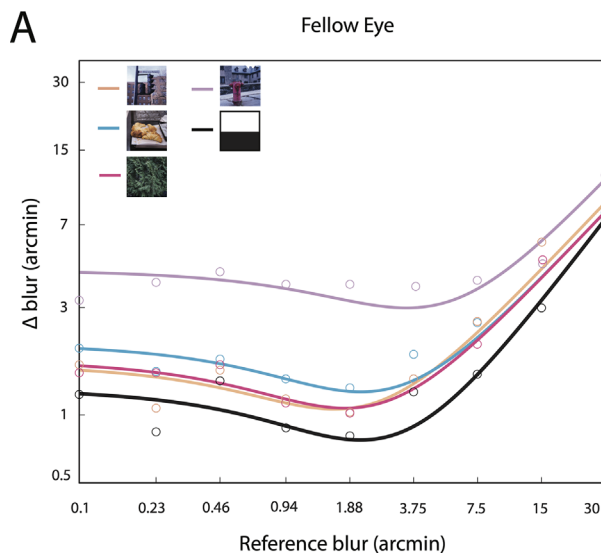


FIGURE 6. (A) Averaged blur discrimination thresholds across subjects for the fellow eye for each image. (B) Averaged blur discrimination thresholds across subjects for the amblyopic eye for each image.

when tested in three out of four natural images: on the street image, $t(11) = -3.661$, adjusted $P < 0.008$, the croissant image, $t(13) = -2.882$, adjusted $P < 0.013$ and the tree image, $t(13) = -2.067$, adjusted $P < 0.039$, with the amblyopic eye exhibiting higher intrinsic blur (Fig. 5A). However, no significant differences in the β parameter were found between the eyes when tested on the hydrant image and the edge (see Fig. 5A). There was no significant difference in the sensitivity parameter ω between the fellow eye and the amblyopic eye for any of the five stimuli tested (see Fig. 5B) suggesting that even if intrinsic blur was heightened when the amblyopic eye was being tested on the street, croissant and tree image, sensitivity to blur differences was not affected.

To better understand these image-specific differences, we calculated a sharpness index of each image based on two distinct methods: a sharpness index based on global phase coherence (GPC)³⁰ and an index using a wavelength domain (WD)³¹ (see Fig. 1). Both methods provided consistent results—the “street” and “leaves” images were consistently found to have the highest sharpness index, followed by the hydrant and the croissant. All-natural images had a higher sharpness index than the edge stimulus, suggesting that differences in blur perception between natural images and edges may be explained in part by their inherent amount of sharpness. However, among natural images, the hydrant—which was the only natural image for which no interocular differences in β parameter were observed—was found

to have a higher sharpness index than the croissant image, suggesting that there is not a strict correlation between blur perception and image sharpness.

Correlation Among β , ω , and Severity of Deficits

We report that the amblyopic deficit is related to both sensitivity and intrinsic blur. A Spearman's rank-order correlation test was run to determine the relationship between the amblyopic subject's visual acuity deficit (measured in terms of their visual acuity difference between the amblyopic and the fellow-fixing eye, in logMAR units) and their mean β parameter difference (difference in intrinsic blur between both eyes) estimated from the dipper function fits to the thresholds aggregated across all natural images. There was a significant correlation between the visual acuity deficit and intrinsic blur ($R_s = 0.638$, $P = 0.035$). The same test was conducted to look at the relationship between the amblyopic subject's visual acuity deficit and their mean ω parameter difference (difference in sensitivity to blur between the two eyes). Again, a significant correlation was also found between visual acuity deficit and sensitivity, which was statistically significant ($R_s = 0.619$, $P = 0.042$). The difference in visual acuity between the amblyopic eye and the fellow eye is therefore correlated with the differences in intrinsic blur and sensitivity, such that as the severity in amblyopia increased, the difference in intrinsic blur and in sensitivity also increased between the eyes. This analysis lends support to our hypothesis that the blur discrimination differences are related to the amblyopic deficit, because they appear to be modulated by the intensity of the deficit.

DISCUSSION

The present study is the first to have investigated blur perception in amblyopia using natural images. Our results indicate that vision through the amblyopic eye is affected by a higher level of intrinsic blur in the visual system compared to the fellow-fixing eye or to healthy eyes when using naturalistic images, but not edges. These results suggest that perceptual losses in amblyopia can be modeled by an increased level of intrinsic blur rather than models based on spatial scrambling. Moreover, because these effects were stimuli specific—in that they were present in natural images only—our results provide a clear demonstration that using synthetic images to test a given visual function may result in performance that is nonrepresentative of these functions under natural conditions.

Higher Levels of Intrinsic Blur in Amblyopia

As reported above, the higher level of intrinsic blur as indicated by a higher β parameter, occurred when the amblyopic eye was being tested on natural images. Interestingly, this difference was not present when tested on synthetic images, replicating earlier reports.⁶ Although it is possible that the lack of difference in response to the edge is due to the amount of data (i.e. the data from 4 images were combined, but there was only one edge stimulus), this is an unlikely explanation—even in post hoc comparisons, we found the amblyopic eye to exhibit greater intrinsic blur for three of four images individually. Thus, it is more likely that natural images are more effective at revealing intrinsic blur than synthetic edges.

The only natural image for which no statistical difference was observed in the level of intrinsic blur between controls and amblyopes was the hydrant image (see Fig. 1 – image 4). However, this lack of difference between the two eyes was not due to a lower level of intrinsic blur when the amblyopic eye was being tested on this image. The hydrant image created as much intrinsic blur when the fellow eye was tested than when the amblyopic eye was tested. These comparable estimates between the two eyes were also significantly higher when compared to the edge (data not shown).

It is difficult to compare our data on image blur discrimination to previous studies, as no study ever investigated blur perception in amblyopia using natural images. Our results using synthetic images are, however, in line with other studies on normal vision using similar design. Indeed Watson and Ahumada²⁸ reviewed several studies on blur perception that used the Weber model to fit their data. Paakkonen and Morgan²² tested healthy subjects and found a level of intrinsic blur (dip value) at about 0.5 to 0.7 arcmin. Wuerger et al. (2001)²⁰ also tested normal subjects and found a level of intrinsic blur at about 1.2 arcmin. Simmers, Bex, and Hess (2003)⁶ tested each eye of both normal and amblyopic subjects and found a similar level of intrinsic blur of about 3 to 4 arcmin in both groups. As in Simmers, Bex, and Hess (2003), we tested each eye of both amblyopic and healthy groups. We found a level of intrinsic blur of about 1.57 arcmin for the fellow eye and of 2.11 arcmin for the amblyopic eye of the amblyopic group, and a level of intrinsic blur of 1.78 arcmin for the dominant eye and of 2.28 arcmin for the nondominant eye of the healthy group, when tested on the edge stimuli. However, those differences did not reach significance, and, as also found by Simmers, Bex, and Hess (2003), we concluded that there was no difference in intrinsic blur between each eye of both healthy and amblyopic groups for the edge stimulus.

Two Main Models: Intrinsic Blur Versus Local Spatial Scrambling

As mentioned in the introduction, the consensus at present suggests that losses occurring in the amblyopic eye may be modeled in terms of either an increased level of intrinsic blur based or as a result of a distorted local spatial scrambling.⁶ Watt and Hess (1987)⁵ proposed that this internal error could be explained, not by raised amounts of intrinsic blur, but by increased spatial scrambling (distorted spatial representations in the visual space), which would imply an elevated degree of relative positional uncertainty in the visual system of anisometric amblyopes. In line with the spatial scrambling model, Simmers, Bex, and Hess (2003) reported no differences in intrinsic blur between the amblyopic and the fellow eye, as well as between the amblyopic eye and the eyes of control subjects. They also found that amblyopes were able to match edges with spatial frequencies that were beyond their resolution limit, results which could not be explained by a neural under-sampling hypothesis as this would predict an increase in blur-discrimination thresholds with an increase in intrinsic blur. Corroborating Watt and Hess (1987), they therefore favored the local spatial scrambling hypothesis, because, according to them, a scrambled edge should retain more information than an undersampled one because the global statistics are preserved and could, in principle, support a veridical global percept.

In their experiments, Levi and Klein (1989),⁴ however, found evidence in support of the intrinsic blur model—their results showed that in amblyopic participants, performance in the fellow eye in the blurred lines condition was equivalent to that of the amblyopic eyes in the unblurred lines' condition suggesting that the amblyopic eye could be mimicked by an increased level of intrinsic blur and contrast.

Our results showing an increase in intrinsic blur in the amblyopic visual system seem to concur those reported by Levi and Klein (1989) and would therefore support a heightened intrinsic blur model of amblyopia. In line with this model, we have also found a positive correlation between the amblyopic subject's visual acuity deficit, their mean β parameter difference (difference in intrinsic blur between both eyes) and their mean ω parameter difference (difference in sensitivity to blur between the two eyes) such that as the severity in amblyopia increased, the difference in intrinsic blur and in sensitivity also increased between the eyes. This correlation lends support to our hypothesis that blur discrimination differences observed in amblyopia are related to the amblyopic deficit itself because they appear to be modulated by its intensity.

Natural Images Versus Synthetic Edge

As mentioned above, we found that in amblyopic participants, intrinsic blur was higher when tested on natural images compared to when tested on the edge. This finding is quite surprising as it is believed that the visual system should be optimized to process natural images, because the spatial organization of the neuron's receptive fields, as well as the tuning characteristics of its individual channels, seem to match the spatial features of the stimuli that are found in the natural environment.^{32–37} One possible explanation for this finding is that as natural images have a higher sharpness index—that is, more numerous fine details scattered throughout the image than in a single synthetic edge. The process of blurring natural images renders the perception of blur less certain than when looking at a single edge. Indeed, studies using natural images suggest that blur is perceived only when the contrast of high frequencies structure falls below that of the low frequencies.³⁸ The more dramatic alteration of the proportions of the power spectrum in blurred natural images than in the case of the blurred simple edges, would therefore explain higher levels of intrinsic blur. Our results tend to validate, in part, this hypothesis as natural images used in our experiment had a significantly higher sharpness index than the single edge stimuli. However, when individual natural images were compared, we did not observe a clear relationship between their overall sharpness and their ability to generate interocular intrinsic blur differences in the amblyopic eye. For instance, blur added to the hydrant image was not able to generate significant intrinsic blur differences in the amblyopic eye even though it had a higher sharpness index than the croissant image, which was the image for which the highest difference in interocular differences was found.

Technical Considerations

Although our study suggests that blur added to natural images is perceived differently than when added to a synthetic edge in amblyopia, the generalizability of our results have to be taken in the context of our experimental design. First, the very nature of blur perception stud-

ies using a staircase approach necessitates a high number of reference blur values for a reliable curve fitting, which generates a high number of staircases in each participant. In our study, a staircase was run for each reference blur, each eye, and each image (90 staircases were run for each participant) leading to lengthy testing times. This limitation did not allow us to test more than four natural images nor to test a greater variety of natural images. Moreover, we did not use a formal selection criterion for the natural images used, rather we sought to ensure that the images were diverse, with different scene composition and color. The reason for the lack of objective selection criteria was again dictated by the fact that we could not test a large variety of stimuli, hence, any criteria would still result in a large number of images, and still some heuristic would have to be used to select the final few images to be used. It is also important to highlight that natural images have been primarily defined as images taken from our natural environment³⁹ and, therefore, the image of a monotonic clear sky with arguably no fine edges is as natural as the image of a highly textured and sharp colorful foliage. Although these images would still be categorized as natural, it is very likely that their distinct visual features would generate distinct blur perception should they have been used in our study. Therefore, whereas stimulus-specific differences reported in our study suggest that testing visual function using artificial stimuli only could result in performances that are nonrepresentative of the visual system under natural conditions,¹⁴ our results should be complemented by further studies using a greater variety of natural stimuli.

Another feature of our experimental design which needs consideration is related to the lack of eye tracking during the task. Although participants could have theoretically moved their eyes, we can assume that they had a stable fixation for the vast majority of the time because clear instructions were given to them to fixate on the fixation cross. Moreover, the random nature of the task itself—to perceptually identify the blurriest of two images which were randomly appearing on the right or left of the fixation cross at random orientations for a very brief period of time (500 ms) did not allow for a given eye movement strategy from the participant. In contrast, the task would theoretically benefit from a stable fixation allowing the participant to see both stimuli with equal eccentricity from the fovea and, thus, random eye movements could have prevented them from performing the task. Finally, our main result—the fact that blur perception differs in the amblyopic visual system—was measured in an interocular manner for both groups. Therefore, even in the unlikely case of significant ocular movements made by participants, these could have occurred in every group and every eye, and so its effect would likely not impact our comparative analysis.

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