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D_{max} for Stereoscopic Depth Perception with Simulated Monovision Correction

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Abstract

Purpose: Persons who wear monovision correction typically receive a clear image in one eye and a blurred image in the other eye. Although monovision is known to elevate the minimum stereoscopic threshold (D_{min}), it is uncertain how it influences the largest binocular disparity for which the direction of depth can reliably be perceived (D_{max}). In this study, we compared D_{max} for stereo when one eye's image is blurred to D_{max} when both eyes' images are either clear or blurred.

Methods: The stimulus was a pair of vertically oriented, random-line patterns. To simulate monovision correction with +1.5 or +2.5 D defocus, the images of the line patterns presented to one eye were spatially low-pass filtered while the patterns presented to the other eye remained unfiltered.

Results: Compared to binocular viewing without blur, D_{min} is elevated substantially more in the presence of monocular than binocular simulated blur. D_{max} is reduced in the presence of simulated monocular blur by between 13 and 44%, compared to when the images in both eyes are clear. In contrast, when the targets presented to both eyes are blurred equally, D_{max} either is unchanged or increases slightly, compared to the values measured with no blur.

Conclusion: In conjunction with the elevation of D_{min}, the reduction of D_{max} with monocular blur indicates that the range of useful stereoscopic depth perception is likely to be compressed in patients who wear monovision corrections.

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Keywords

D_{max}, monovision, monocular blur, stereopsis, D_{min}

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1. Introduction

The ability to change focus in order to see clearly at near distances gradually diminishes with age. This condition is called presbyopia. Monovision is a common means of correction for presbyopia, whereby one eye is corrected for distance vision and the fellow eye is corrected for near vision using contact lenses, refractive surgery or intraocular lenses. For most viewing distances, monovision wearers receive a clear image in one eye, and a blurred image in the other eye.

A reduction of stereopsis, the ability to make precise judgments of relative depth from small differences between the images in the two eyes, is one of the major side effects for people who wear monovision corrections (Godts *et al.*, 2004; Lebow and Goldberg, 1975; McGill and Erickson, 1988). The range of stereopsis is defined by the lower and upper thresholds for binocular disparity, D_{min} and D_{max}. Between D_{min} and D_{max} the direction of relative depth can be perceived reliably. Unequal blur of the images in the two eyes is known to degrade D_{min} by a greater amount than when the images in both eyes are blurred equally (Hess *et al.*, 2003; Lit, 1968; Patel *et al.*, 2006; Schmidt, 1994; Westheimer and McKee, 1980; Wood, 1983). In part, this may be due to unequal image contrast, which reduces stereoacuity even for images with matched spatial frequency content (Legge and Gu, 1989; Schor and Heckman, 1989; Stevenson and Cormack, 2000), although this 'contrast-paradox' effect is most pronounced at low spatial frequencies (Cormack *et al.*, 1997). It is less clear how unequal image blur influences D_{max}. One possibility is that D_{max} increases in the presence of monocular blur, as the value of D_{max} for motion perception is reported to be dependent on the upper cut-off spatial frequency of the stimulus (Cleary and Braddick, 1990). There are close parallels between the processing of motion and stereopsis (Glennerster, 1998), and the highest common spatial frequency in the images seen by two eyes is decreased in monovision. An alternative possibility is that monocular blur produces a generalized impairment of stereoscopic processing, with a decrease in D_{max} in addition to an increase in D_{min}. Impaired stereopsis may result from the dissimilarity of the two images that occurs during monocular blur, which should increase the likelihood of false matches (Glennerster, 1998).

To more completely understand the influence of monovision correction on stereopsis, this study compared both D_{min} and D_{max} for stereopsis when one eye's image is blurred *vs.* when the images in both eyes are either blurred by equal amounts or are clear.

2. Methods

The stimuli were created using Matlab (MathWorks, 2006) and the Psychophysics toolbox (Brainard, 2003), generated by a VSG 2/3 graphics card (Cambridge Research Systems), and presented on a 20 inch CRT monitor (Clinton DS2000) with a resolution of 864 by 644 pixels. The graphics card was synchronized with FE-1 ferro-electric stereo-goggles (Cambridge Research Systems) that provided independent stimulation of each eye at a temporal frequency of 60 Hz.

Six subjects participated in the experiment. All subjects had normal or corrected-to-normal vision, and at least 40 arc s of stereopsis measured by the Titmus stereo test (Titmus Company Inc., Petersburg, VA) in both the crossed and uncrossed directions. The numbers of subjects who completed each condition varied, and are indicated in legends of Figs 3 and 4.

2.1. Stimuli

The stimuli were pairs of vertically oriented, random-line patterns, presented simultaneously for 500 ms above and below a fixation cross (Fig. 1). Stimuli were presented on the Clinton monochrome display, which had a 21.6° horizontal extent when viewed from a distance of 97 cm. At this viewing distance, each spatially unfiltered random line was 3 min wide by 8° tall. Subjects viewed the display binocularly through ferromagnetic shutter goggles that were synchronized to the monitor frame rate of 120 Hz. Control observations, in which one eye viewed a random-line pattern and the other eye viewed a uniform grey screen, confirmed the absence of cross-talk between the disparate random line images that were presented to each eye.

In different blocks of trials the density of the unfiltered random lines was either 5 or 20% of the screen area. Stimuli included equal numbers of dark and light lines with the same absolute Weber contrast, to ensure that the mean luminance of the stimulus (11.5 cd/m^2 as viewed through the shutter goggles) was the same for both line densities. The Weber contrast of the unfiltered upper lines was $\pm 62.5\%$. The lower lines had a fixed root-mean-square (RMS) contrast of 0.1 (RMS contrast = standard deviation of luminance/mean luminance), so that the stimuli with different line densities contained the same amount of contrast energy. Binocular correlation was restricted to the central 14.4° of the upper line stimuli, in order to prevent da

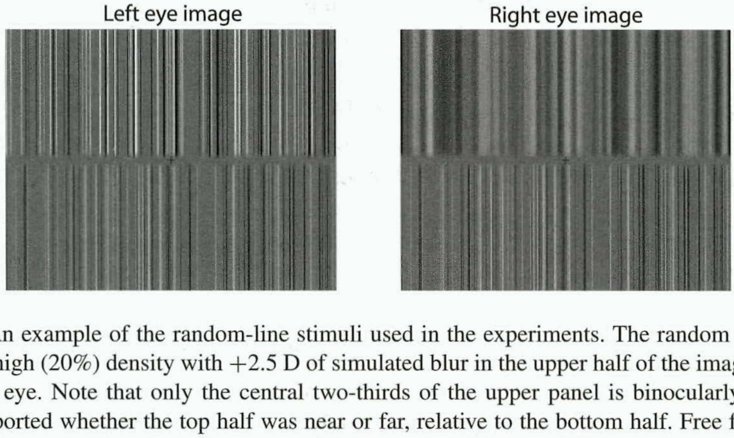

Figure 1. An example of the random-line stimuli used in the experiments. The random lines shown here are of high (20%) density with +2.5 D of simulated blur in the upper half of the image presented to the right eye. Note that only the central two-thirds of the upper panel is binocularly correlated. Subjects reported whether the top half was near or far, relative to the bottom half. Free fusion of the left and rights panels provides a simulation of the monocular blur condition.

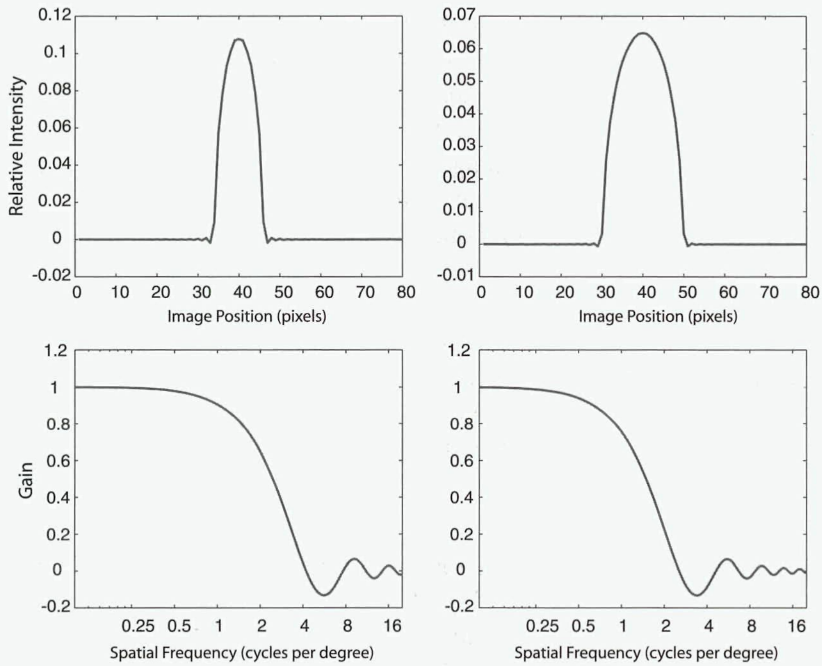

Figure 2. Blurring of the random-line stimuli was accomplished by convolution of the unblurred lines with one of two blur functions, with the spatial kernels illustrated in the upper panels. This resulted in low-pass-filtered patterns with the average spectra shown in the two lower panels (+1.5 D of blur on the left and +2.5 D on the right).

Vinci stereopsis (Nakayama and Shimojo, 1990). More peripheral regions of the upper random-line stimulus were uncorrelated in the two eyes.

To simulate monovision correction, the random-line patterns presented to either the left or right eye were low-pass spatially filtered and the patterns presented to the other eye were unfiltered. To simulate +1.5 or +2.5 D of optical blur, each random-line pattern was convolved with the appropriate blurring filter (cf. Akutsu *et al.*, 2000) by multiplication in the Fourier domain using Matlab (see Fig. 2). Each blurring filter was calculated assuming a pupil diameter of 4 mm. Binocular image disparity was produced between the upper images presented to the left and right eyes by introducing a spatial phase shift proportional to the spatial frequency of each Fourier image component (range = 0.05–20 cpd; Patel *et al.*, 2003). The lower line stimuli were unfiltered, and were always presented at zero disparity.

2.2. Procedures

The subject initiated each trial with a button press. After each 500-ms stimulus presentation, the subject reported with another button press whether the upper line pattern was nearer or farther than the lower line pattern. A new random-line pattern was generated on each trial. To assess $D_{\min}$, 10 trials were presented at each of 9 disparities (4 crossed, 4 uncrossed and zero). To assess $D_{\max}$, 10 trials were presented for each of 8 disparities in the crossed and uncrossed directions and the numbers of correct responses for the two directions were pooled. The resulting data sets were fitted by cumulative Gaussian functions using the curve-fitting toolbox in Matlab. D_{min} was defined as the SD of the fitted psychometric function, corresponding to a change in the percentage of 'crossed' or 'uncrossed' responses from 50–84%. D_{max} was defined as the maximum image disparity corresponding to 75% correct responses on the fitted psychometric function.

2.3. *Data Analysis*

Data were analyzed by applying a repeated-measures mixed-model analysis using an autoregressive correlation matrix. The analyses were performed in SPSS. The denominator degrees of freedoms that are reported are rounded to the nearest integer. Comparisons between specific conditions were performed subsequently using paired *t* tests.

2.3.1. D*min*

The model consisted of two main factors (blur type: no blur, both eyes, left eye and right eye; blur magnitude: +1.5 and +2.5 D). The interaction term included in the analysis was blur type × blur magnitude. Other factors and their interaction terms were not significant and were iteratively removed from the model.

2.3.2. D*max*

The model consisted of three main factors (blur type: no blur, both eyes, left eye and right eye; blur magnitude: +1.5 and +2.5 D; line density: 5 and 20%). The interaction terms included in the analyses were blur type × blur magnitude and blur type × line density. Other interactions were not significant and were iteratively removed from the model.

3. Results

In the absence of blur, the observers' average values of D_{min} are 16 ± 2.5 (SE) and 13 ± 2.2 arc s for stimuli with 5 and 20% line densities, respectively. The line density of the stimuli exerts no systematic effect on D_{min}. In agreement with previous findings (Chen *et al.*, 2005; Lit, 1968; Patel *et al.*, 2006; Schor and Flom, 1969; Westheimer and McKee, 1980; Wood, 1983), D_{min} is elevated more in the presence of monocular compared to binocular stimulus blur (Fig. 3). For plotting, each subject's thresholds for monocularly and binocularly blurred stimuli were normalized with reference to the value of D_{min} without blur. A repeated-measures analysis revealed significant main effects of blur type ($F[3,42] = 16.5$, $p < 0.001$) and blur magnitude ($F[1,17] = 11.8$, $p = 0.003$). Additionally, there is a significant interaction between blur type and blur magnitude ($F[3,43] = 9.8$, $p < 0.001$). Specifically, across both line densities the average percent change in D_{min} is 42% with +1.5 D of simulated binocular blur and 290% with +1.5 D of simulated monocular blur (averaged for right-eye and left-eye blur conditions; compared to

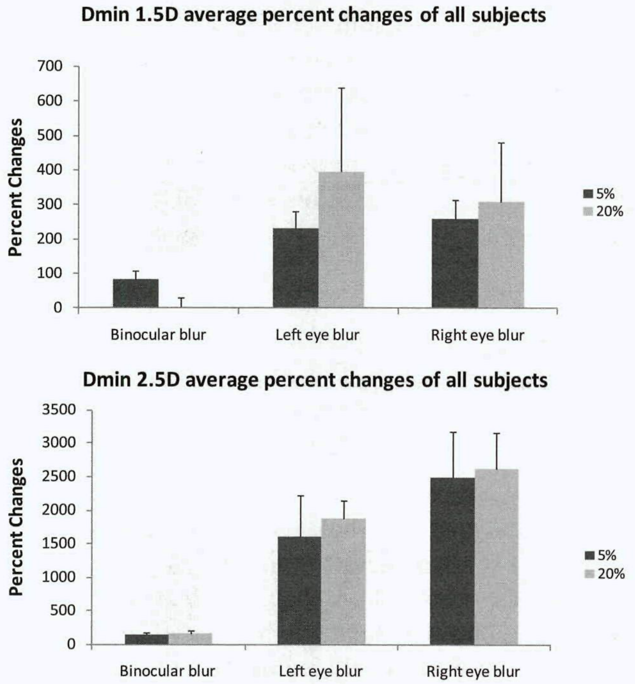

Figure 3. D_{min} for monocularly and binocularly blurred stimuli were normalized for each subject with reference to the value of D_{min} without blur. Taller bars indicate worse stereoscopic performance. Percentage changes were averaged across subjects for +1.5 D (top panel) and +2.5 D defocus (bottom panel). The data from 4 and 6 subjects contribute to the plotted averages for the +1.5 D and +2.5 D condition, respectively. Notice the difference in y-axis scaling between the two panels. Black and gray bars are for 5 and 20% density random lines, respectively. Error bars indicate between-subject standard errors.

binocular blur, $t[3] = 2.93$, $p = 0.061$). When the amount of simulated blur is increased to +2.5 D, D_{min} is elevated even more, to 149% and 2027% of the unblurred threshold for targets with binocular and monocular blur, respectively (for monocular compared to binocular blur, $t[5] = 4.36$, $p = 0.007$).

The subjects' average values of D_{max} with binocularly unblurred targets are 86 ± 7.7 (SE) and 75 ±12.6 min arc for the stimuli with 5 and 20% line densities, respectively. These results are comparable to previously published values of D_{max}, determined with 50% density dynamic random dots (Stevenson and Schor, 1997). Figure 4 illustrates that monocular blurs *reduces* D_{max}. Although the main effects of line density and blur magnitude are not significant (line density: $F[1,47] = 1.5$, $p = 0.226$; blur magnitude: $F[1,21] = 0.009$, $p = 0.926$), there is a significant main effect of blur type ($F[3,52] = 42$, $p < 0.001$). Additionally, there are significant interactions between blur type and blur magnitude ($F[3,48] = 5.9$, $p = 0.002$) and between blur type and line density ($F[3,50] = 3.3$, $p = 0.027$). As shown in Fig. 4, D_{max} is reduced in the presence of simulated monocular blur by between 13 and 44%, compared to when the images in both eyes are clear (averaged for right-eye

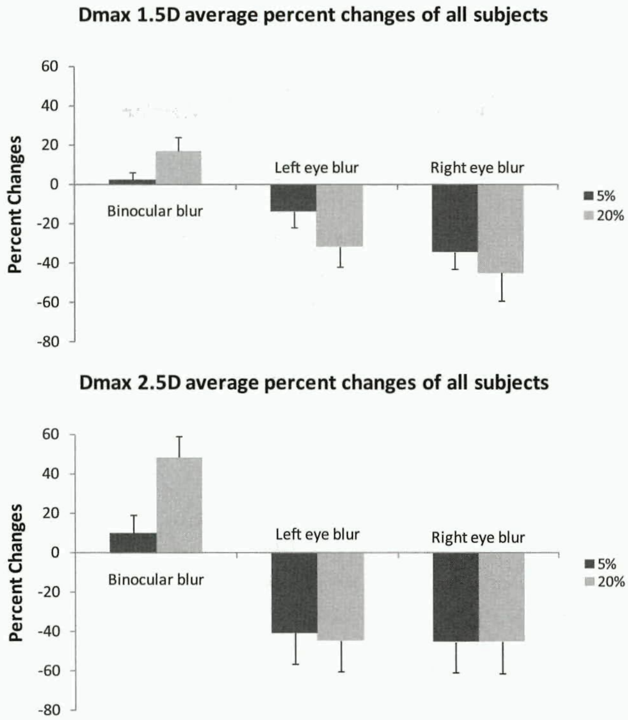

Figure 4. D_{max} for monocularly and binocularly blurred stimuli were normalized for each subject with reference to the value of D_{max} without blur. Negative values indicate a reduction in the range of stereoscopic vision. Percentage changes were averaged across subjects and plotted for +1.5 D (top panel) and +2.5 D defocus (bottom panel). The results for both the +1.5 and +2.5 D conditions include the data of 5 subjects.

and left-eye blur conditions, $t[5] = 3.80$, $p = 0.019$). The reduction of D_{max} is not significantly larger with +2.5 D compared to +1.5 D of simulated monocular blur ($t[df = 3] = 2.36$, $p = 0.099$). When the targets presented to both eyes are blurred equally, D_{max} remains essentially unchanged for the low-density stimuli but *increases* significantly for the high-density line stimuli ($t[df = 4] = 4.58$, $p = 0.010$), compared to the corresponding stimulus condition with no blur.

4. Discussion

As already noted above, the greater increase in D_{min} with monocular compared to binocular simulated blur is consistent with previous findings (Hess *et al.*, 2003; Lit, 1968; Patel *et al.*, 2006; Westheimer and McKee, 1980; Wood, 1983). Our data show that monocular image blur also reduces D_{max}, compared to the values obtained with no blur, or to when equal amounts of blur are added to the images in the two eyes. Jimenez *et al.* (2008) reported that D_{max} for stereopsis decreases in patients who undergo bilateral Lasik surgery and that the magnitude of this decrease is related to the between-eye difference in residual ocular aberrations, i.e., the amount of interocular blur. Earlier, Hess *et al.* (2003) compared the influence of binocularly equal and unequal low-pass spatial filtering on D_{max} for two-dimensional fractal noise patterns and reported that D_{max} was approximately 30 min arc for both of these conditions. However, in this study binocular disparities were presented only within a 1-deg circular field, which may have limited the measured values of D_{max} for both equal and unequal low-pass filtering.

The increase of D_{min} and the reduction of D_{max} with monocular blur indicate that the range over which stereoscopic depth can be veridically perceived is likely to be compressed in patients who wear monovision corrections. Assuming the average value of D_{max} of 82 min arc in the no-blur condition and a viewing distance of 40 cm, the depth interval within which veridical stereoscopic vision is possible (i.e., crossed D_{max} to uncrossed D_{max}) ranges approximately from 34.8 to 46.9 cm (Fig. 5). If D_{max} decreases to 46 min arc with monocular image blur, then the linear depth interval is reduced to between 36.9 and 43.6 cm. Because the linear depth interval varies roughly with the square of the viewing distance (Schor and Flom, 1969), the reduction of D_{max} with monocular blur produces a more pronounced effect on the depth interval for distance targets. At a viewing distance of 4 m, the linear depth interval corresponding to a D_{max} of ± 82 min arc ranges from 1.6 m to infinity. A reduction of D_{max} to ± 46 min arc in the presence of monocular image blur reduces the linear depth interval to between 2.2 and 22.7 m. Analogously,

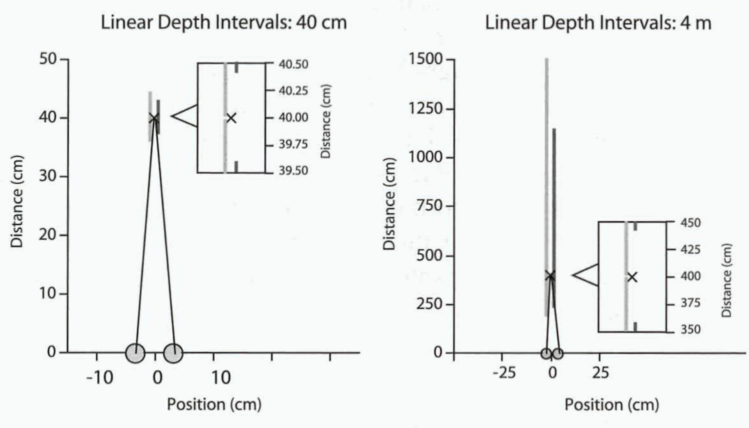

Figure 5. The effect of monocular blur on the linear depth interval is represented. The calculation of linear depth intervals using the average measured values of D_{max} is based on formulae given by Schor and Flom (1969). The two eyes are shown at the bottom of each panel. Vertical bars indicate the useful range of binocular stereoscopic vision for unblurred (left of the fixation '×') and monocular blurred (right of the fixation '×') conditions, for near (left panel) and far (right panel) viewing distances. Within each panel, the inset illustrates the effect of monocular blur on the linear depth required to exceed the lower stereoscopic threshold (D_{min}). Note the difference in horizontal and vertical scales in the two panels and in the insets. In the right panel the distal extent of the linear depth interval for the unblurred condition is truncated at 1500 cm. The reduction of D_{max} with monocular blur has the effect of reducing the useful range of binocular stereoscopic vision. This figure is published in color in the online version.

a change from no stimulus blur to monocular blur (+2.5 D) degrades D_{min} from 0.24 to 5.33 arc min. Therefore, at a viewing distance of 40 cm, a stimulus can be seen veridically in depth when it is separated by more than ±0.017 cm from the fixation target in the no-blur condition, and by more than ±0.39 cm in the presence of monocular blur. To be seen in depth when the viewing distance increases to 4 m, a target must be more than ±1.7 cm from the fixation stimulus in the no-blur condition, and approximately ±38 cm with monocular blur.

'Phase-based' and 'information-based' hypotheses have been proposed for the determination of D_{max}. The 'phase-based' hypothesis proposes that binocular disparity is processed within each spatial-frequency tuned detector before the responses of these different detectors are combined (Cleary and Braddick, 1990; Eagle and Rogers, 1996; Prince *et al.*, 2002). Each detector is only able to detect the disparity of a specific spatial frequency component up to a critical phase shift, which is necessarily less than 180°. Therefore, according to this hypothesis D_{max} is limited by the spatial frequency spectrum of the stimulus. On the contrary, the 'information-based' hypothesis holds that the matches between corresponding features occur after the outputs from individual spatial frequency filters are combined. In feature-matching models, the correct detection of depth is limited by the spacing of the features in the stimulus, because the correspondence problem becomes more difficult to solve as the potential number of false target matches increases (Glennerster, 1998).

In addition to removing high spatial frequencies from the image, blur also increases the average spacing between feature primitives, although this should be less important for low- than for high-density targets (see Note 1). Therefore, our observation that D_{max} increases with binocular image blur compared to the no-blur condition can be explained by either the 'phase-based' or 'information-based' hypothesis. Our data indicate also that D_{max} decreases in the presence of monocular image blur compared to the no-blur condition. The 'information' hypothesis provides a possible explanation for this outcome, as monocular blur reduces the similarity of the two images and results in an increased number of potential false stereoscopic matches.

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Note

1. In random-line patterns, the peaks, troughs and edges are usually considered to be the features used for matching. After a pattern is filtered, the feature spacing cannot be smaller than the spatial period of the high spatial frequency cut-off of the blurring (low-pass) filter.

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