Perceptual quality of reconstructions of digital holograms: extending depth of focus by binocular fusion

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Introduction: Reconstructions of digital holograms have a very shallow depth of focus. In order to obtain a perceptually greater depth of focus, we explored a computationally simple approach, suggested by Lehtimäki and Naughton [3DTV Conference 2007; IEEE Press, New York (Kos, Greece)], where the perceptual depth of focus is obtained by dichoptic viewing of near focused and far focused holographic reconstructions. In the dichoptic viewing arrangement one eye sees a near focused and the other a far focused image. Because of binocular fusion we see a blend of the two images, in which the perceptual sharpness is far more uniform than in each of the images alone. In this experiment, *we sought an answer to the question of to what extent does each dichoptically presented image contribute to the perceived sharpness of the binocularly fused image.*

Method: For dichoptic presentation of stimuli we used a stereoscopic display (24´ Hyundai W240S), which was viewed with circular polarising glasses. On the left half of the display the subjects saw the near and far focused images dichoptically, which by binocular fusion produced a perceptually increased depth of focus. On the right half of the display they saw a computationally fused image, which consisted of locally weighted averages of the near and far focused images. The computational fusion was obtained by using Equation 1. In Equation 1, exponent p varied from -4 to +8 with steps of 0.5. When p is equal to zero, the equation reduces to an ordinary arithmetic mean. When p is above zero the high value of the rms contrast, i.e. sharp image, is emphasised relative to a low value of rms contrast, i.e. blurred image. When p is negative the blurred image is emphasised relative to the sharp image. Thus, the series of values of exponent p gave a series computationally fused images, where sharpness varied from blurred to sharp.

In the experiment, the observer could vary the sharpness of the computationally fused image in real time by using a graphical slider. The task of the observers was to match the computationally

Equation 1:

$$I_{fused}(x,y) = \frac{|C_{left}(x,y)|^{p}\, I_{left}(x,y) + |C_{right}(x,y)|^{p}\, I_{right}(x,y)}{|C_{left}(x,y)|^{p} + |C_{right}(x,y)|^{p}}$$

where $I_{left}(x,y)$ and $I_{right}(x,y)$ are the images received by the left and right eyes, respectively. Local root-mean-square (rms) contrasts of the left and right eye images, $C_{left}(x,y)$ and $C_{right}(x,y)$ shown in Figure 2, represent the high spatial frequency content in the images, and therefore reflect sharpness.

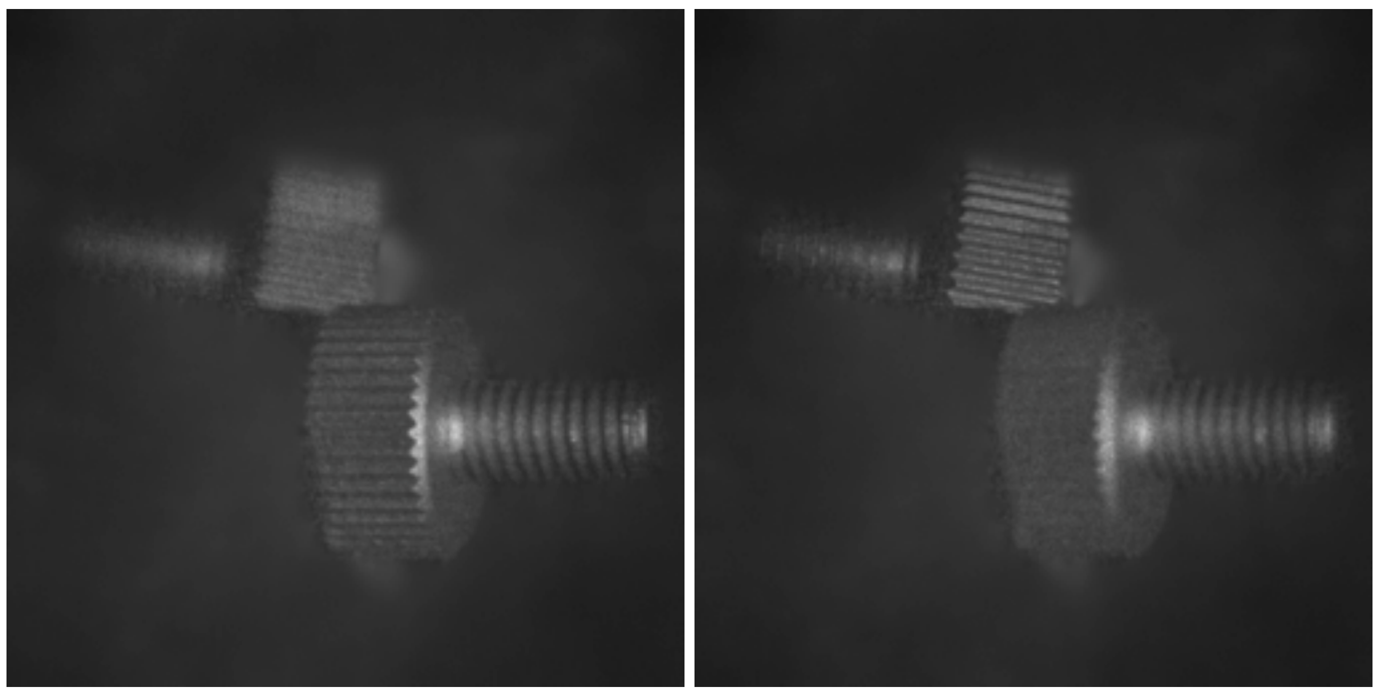

Figure 1. Near focused and far focused images.

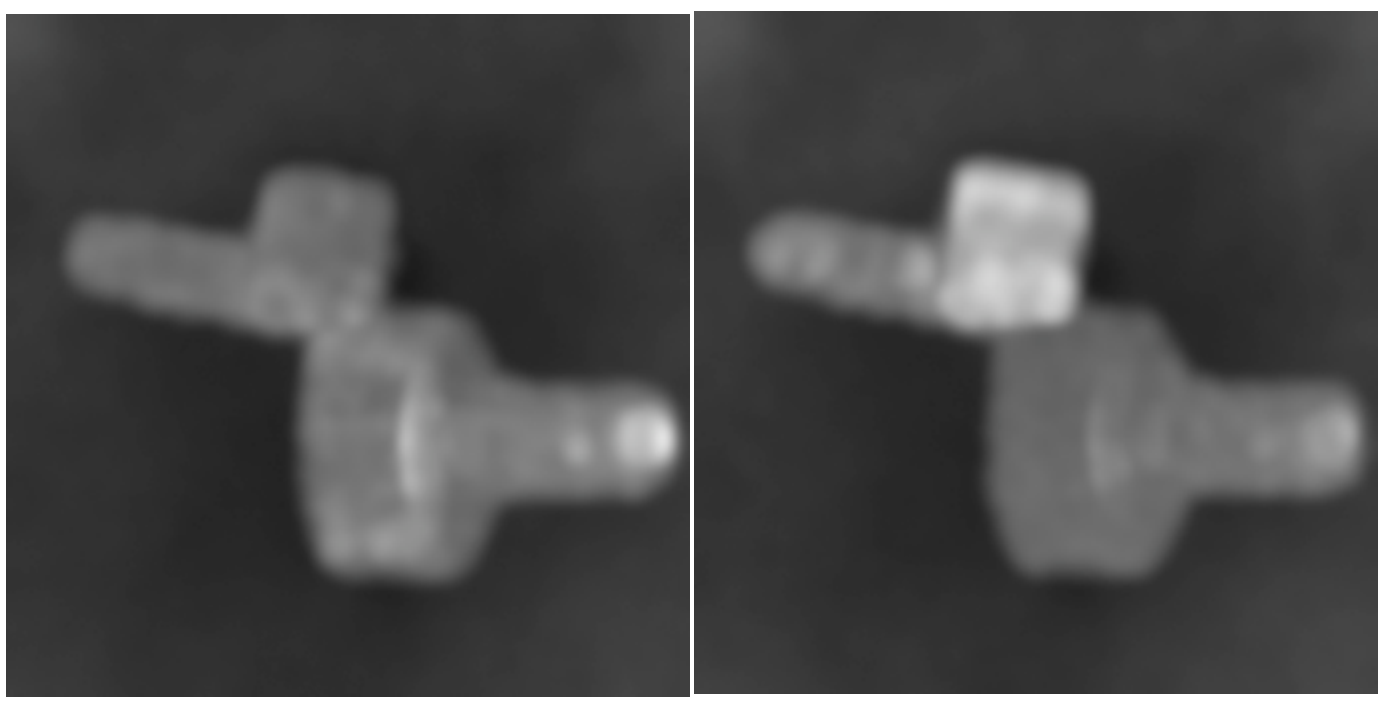

Figure 2. Contrast maps for the near and far focused images.

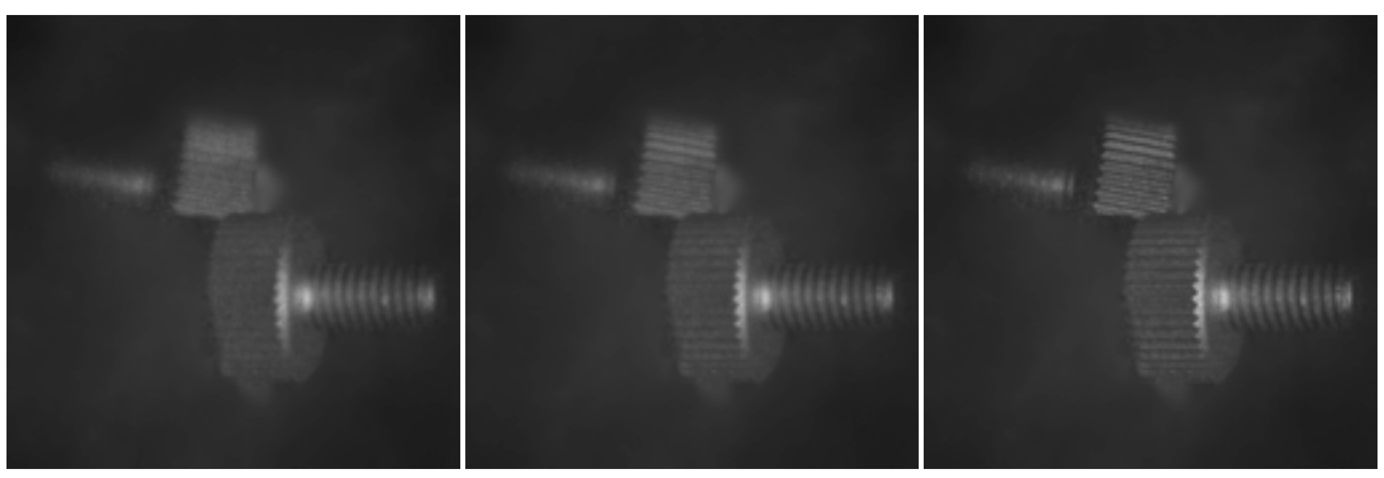

Figure 3. Examples of computationally fused images. The values of p are -4, 0, and +8 from left to right.

fused image to the binocularly fused image with respect to perceived sharpness. Each measurement consisted of 20 matches. Measurements were made for two viewing distances, 150 and 300 cm. The image size was 24.6 x24.6 cm^2. Thus, the images were seen in visual angles of 9.4 and 4.7 deg at the distances of 150 and 300 cm, respectively.

Results and conclusions: The results are shown in Figure 4 A and B. The matches for each observer are presented as cumulative distributions of exponent p of the computational fusing function. All values of exponent p are clearly above zero. This suggests that in the perception of the binocularly fused image, the in-focus areas of each image, i.e., the sharp parts, had a relatively greater contribution than the out-of-focus areas, i.e. the blurred parts. However, the dominance of in-focus areas was not complete. The fused perception seemed to correspond to a point-wise weighted mean of the dichoptic image pair where the weighting is dependent on the local high spatial frequency contrast of the near and far focused images. The extent to which sharp image is emphasized relative to blurred image varied across individuals. Thus, there appears to be observer dependent differences in binocular fusion.

In Figure 5, we have studied the binocular fusion for overall contrast. The task of the observer was to match the contrast of a binocularly presented image to a stimulus where one eye saw a similar image and the other eye saw a zero contrast image. The median matched binocular contrast computed across observers was practically identical to the contrast seen by one eye. In Equation 1, the zero contrast image has a zero weight, and, therefore, the fused image is the same as the non-zero image. The binocularly fused image is also identical to the image presented to one eye. Thus, the experimental result is in agreement with Equation 1. However, there is variability in the results across observers and conditions.

The results suggest that the binocular fusion of complex images can be modeled as a point-wise weighted mean of images seen by the two eyes so that the weight at each position is the local high spatial frequency contrast of each image raised to a power greater than zero. The value of the exponent varies across individuals to some extent. The results also show that dichoptic presentation of near and far focused images may be a useful and simple way to extend the depth of focus of holographic reconstructions.

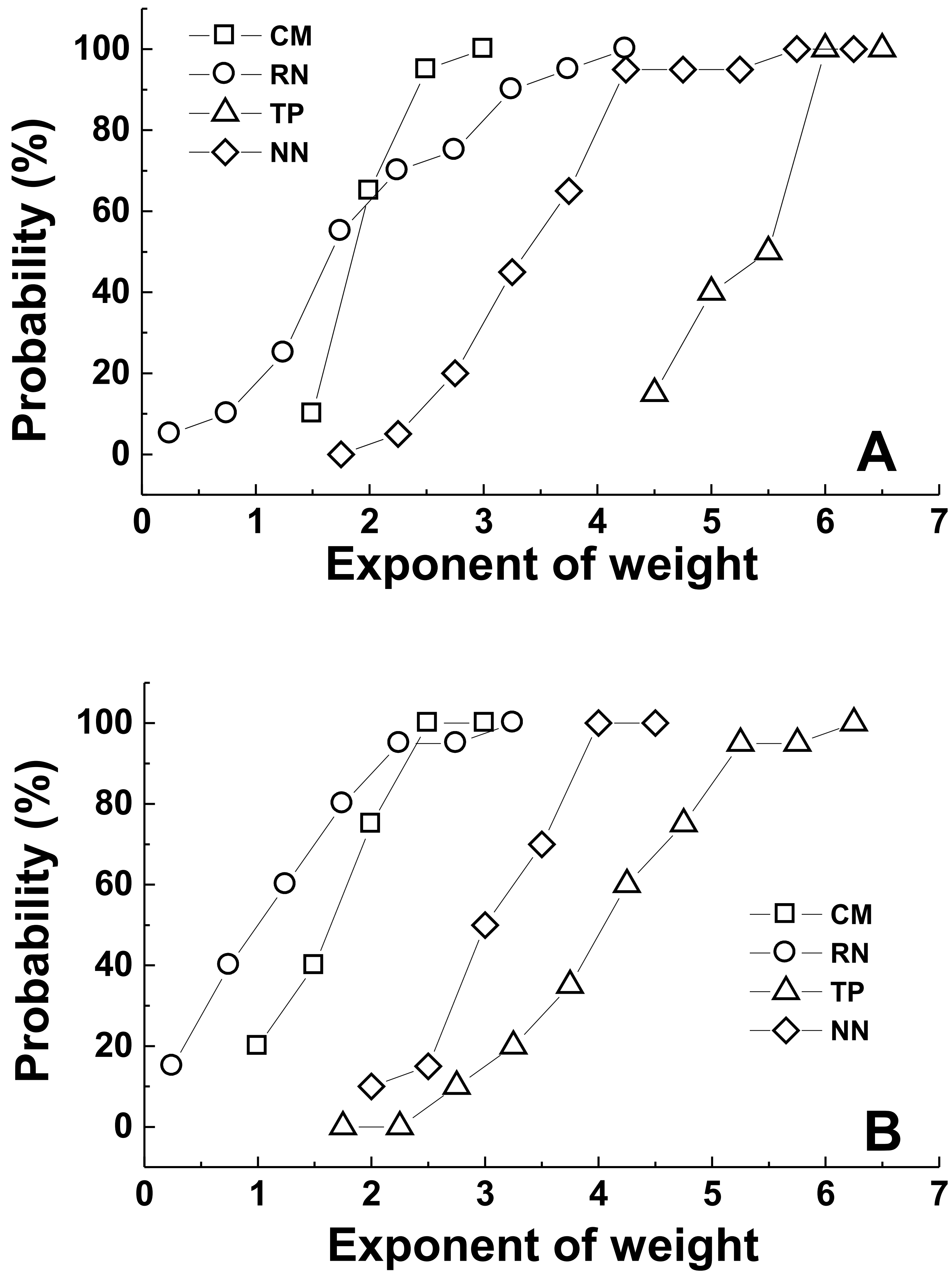

Figure 4. Cumulative distributions of perceived sharpness matches between binocularly fused and computationally fused images presented as cumulative distributions of the exponent of weight. In Figure A, the viewing distance was 150 cm and in B it was 300 cm.

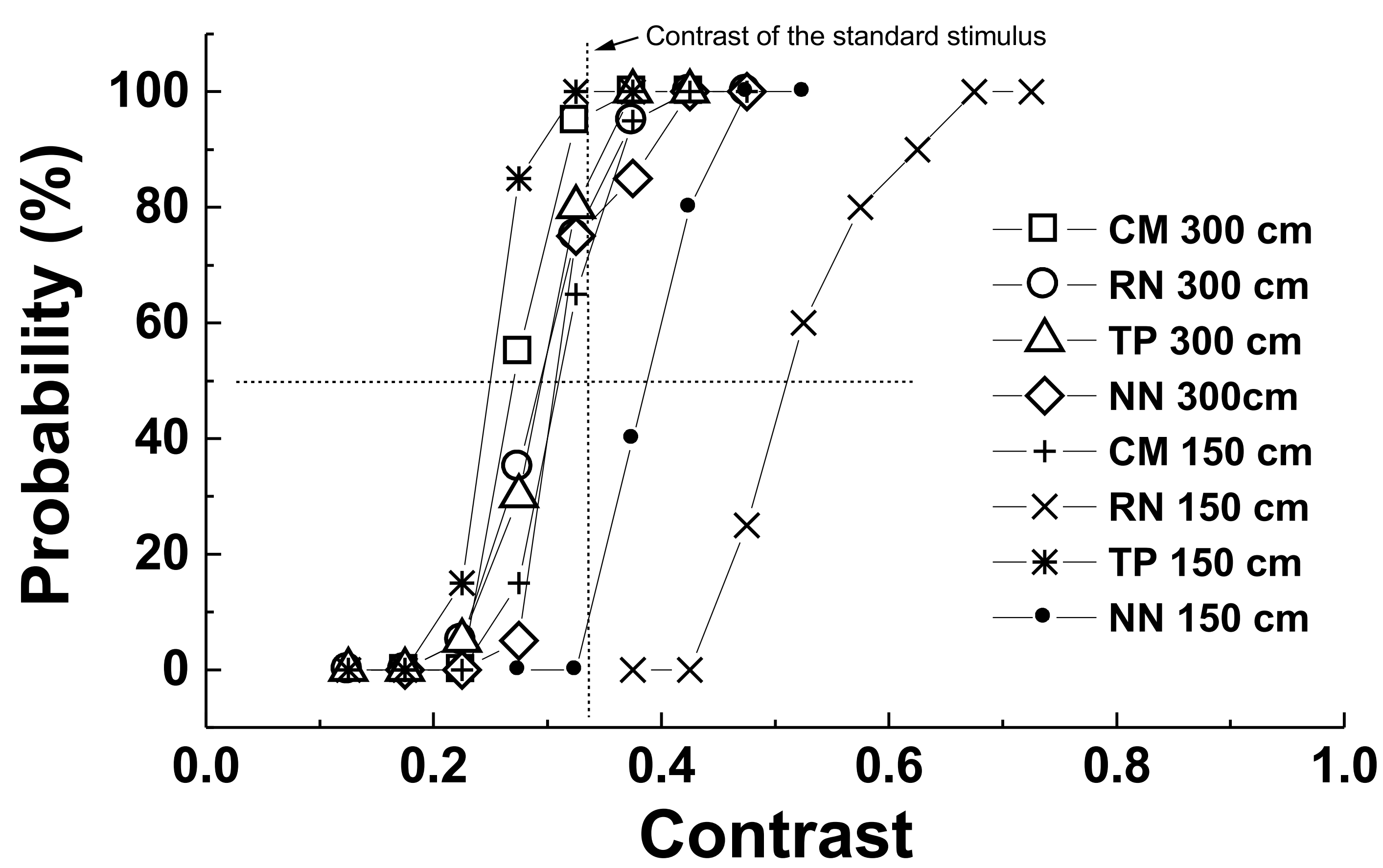

Figure 5. Cumulative distributions of perceived contrast matches. The contrast of a binocularly presented image was matched to stimulus where a similar image was seen by one eye and zero contrast image by the other eye.