Chapter 6

Is it possible to realistically render blur?

There are two different ways of presenting blurred stimuli. Firstly, the blur can be introduced optically, so that it interacts naturally with the aberrations of the observers eye. For example, this can be done using lenses or a deformable mirror, or even by simply altering the distance between the target and the observer. In this chapter I will refer to blur introduced in this way as optical blur (it has also been described as "observer blur" in past literature). Alternatively, the blur can be rendered in the stimulus itself, for example by convolving the stimulus with a blur disc or point spread function (PSF). The blur presented by this second method will not interact naturally with the aberrations of the eye and may not result in a realistic retinal image depending on how the blur is rendered. In this chapter I will refer to this as rendered blur (it has also been described as "source blur" in some papers).

It would be very useful to be able to render blur realistically as an alternative to introducing the blur optically. This is because in many ways it is simpler to render blur than to optically induce blur. Optically blurring a stimulus requires specialised equipment such as lenses or a deformable mirror. There is also the issue that the eye can accommodate to counteract the optically induced defocus blur meaning that often the accommodation of the eye will need to be controlled or prevented to get the desired blurred image on the retina. Typically, optically blurred images can also only be presented to one observer at a time as the observer will need to be aligned with the optical set-up. Rendered blur, on the other hand, could potentially avoid these complications.

The ability to render blur effectively could be useful in creating realistic simulations of scenes (e.g. for virtual reality). In real scenes not all objects will be in focus at one time. Therefore to make a two dimentional scene appear realistic the objects that are not in the focal plane will need to be blurred. It may be that the more realistic this blurring is, the more realistic the scene appears to be. In fact Cholewiak et al. (2017) found this to be the case when the rendered blur in a scene was made more realistic by including the chromatic aberration of the eye.

Creating realistic blur could also be useful in more clinical settings. For example, when fitting glasses, contact lenses, or even intra-ocular lenses, it could allow patients to view how certain types of optical correction might effect their vision before they are manufactured and, in the case of intra-ocular lenses, inserted.

Making comparisons between optical and rendered blur is also of interest from a more theoretical perspective. By exploring which factors must be accounted for in order to render blur realistically, we can develop an understanding of how much of an impact different optical features have on our perception of blur and our visual acuity (VA), and which types of blur we are more able to tolerate. It may also give us an insight into which features improve the eye's tolerance to blur.

6.1 Previous Studies

A number of previous experiments have been conducted comparing the effects of optical and rendered blur on VA (Smith et al., 1989; Jacobs et al., 1989; De Gracia et al., 2009; Dehnert et al., 2011; Ohlendorf et al., 2011; Remón et al., 2014). The general trend in these studies has been that we appear to be more tolerant to optical blur than rendered blur, with rendered blur reducing the VA more than the supposedly equivalent amount of optical blur. However, this effect was not always significant.

We have created a table to summarise a selection of previous studies (Table 6.1). This table is colour coded according to whether or not a significant difference was found between rendered and optical blur. The ones highlighted in green found that the VA was significantly better for optical than rendered blur. The ones highlighted in amber found mixed results, with some experiments showing a significant difference between rendered and optical blur and others showing no significant difference. However, for all of the studies highlighted in amber the trend, even in the non-significant experiments, was for rendered blur to reduce VA more than optical blur. The Dehnert et al. (2011) study, highlighted in red, is the one exception to this rule. In this study no significant effect was found, and VA was actually slightly better for rendered blur than for optical blur, which is opposite from the trend shown by the other studies.

Another trend from this data is that there is a greater difference between optical and rendered blur for astigmatism than for defocus. Both Ohlendorf et al. (2011) and Remón et al. (2014) found significant effects for astigmatism and astigmatism plus defocus. However, for defocus alone the results were not generally significant. Dehnert et al. (2011) only investigated defocus and not astigmatism. This could help to explain the differences in their findings from other studies.

In the cases where rendered blur reduced VA more than optical blur, there must have been some aspect of the optically induced blur not captured by those methods for rendering blur, making us more tolerant to the optical blur. Smith et al. (1989) and Jacobs et al. (1989) used a simple blur disk with a uniform luminance as the blur kernel. This is quite different from the actual PSF of an eye and therefore it is not surprising that there was a discrepancy between the effects of the rendered and optical blur. De Gracia et al. (2009), Dehnert et al. (2011), Ohlendorf et al. (2011) and Remón et al. (2014), on the other hand, all generated PSFs based on the magnitude of the defocus (or astigmatism) and the pupil size. It is therefore necessary to investigate further why all but Dehnert et al. (2011) still found a significant difference between the effects of optical and rendered blur. A number of different factors have been suggested as the cause for this discrepancy. These are possible factors are discussed below.

1. One possible explanation is that the observers were able to partially accommodate to the stimuli. This could have reduced the blur from the optical defocus and also potentially from the optical astigmatism. Three

Table 6.1: Summaries of a selection of previous studies. The table is colour coded to indicate whether a significant difference was found in the effect on VA between the two blurring methods. Green indicates that there was a significant difference found, red indicates that there was no significant difference found and orange indicates that there were mixed results with significant effects found for some experiments but not others.

	Smith et al. (1989)	**Jacobs et al. (1989)**	**De Gracia et al. (2009)**	**Dehnert et al. (2011)**	**Ohlendorf et al. (2011)**	**Remón et al. (2014)**
Significant difference	Yes • VA sig. worse for ren blur	Mixed • **Blur threshold:** Sig less ren blur needed • **Blur JND:** No	Yes • VA sig. worse for ren blur	No	Mixed • **Defocus:** No • **Astigmatism:** VA sig worse for ren blur • **Cross-cylinder:** VA sig. worse for ren blur	Mixed • **Defocus:** No • **Astigmatism:** Sig less ren blur needed • **Mixed astigmatism:** Sig less ren blur needed
Stimuli	Landolt C	Landolt C	Landolt C	Landolt C	Landolt C	Landolt C
Type of blur	Defocus	Defocus	Natural aberrations	Defocus	Defocus and astigmatism	Defocus and astigmatism
Blur disc	Circular blur disc with uniform luminance	Circular blur disc with uniform luminance	Realistic PSF based on magnitude of aberrations and pupil size	Realistic PSF based on magnitude of aberrations and pupil size	Realistic PSF based on magnitude of aberrations and pupil size	Realistic PSF based on magnitude of aberrations and pupil size
Preventing accommodati on	Cyclopleged for optical blur condition	Cyclopleged for optical blur condition	NA	Target at infinity	Target at 4m	Target at 5m
HOAs accounted for	No	No	Yes • Rendered HOAs • Corrected real HOAs for rendered blur	No	No	No
Stiles Crawford effect	NA	NA	Unknown	Yes	Unknown	Unknown
LCA accounted for	No	No	Unknown	Yes • Narrowband light	No	No
Pupil	Artificial pupil for optical blur	Artificial pupil for optical blur	Artificial pupil	Natural pupil	Artificial pupil	Natural pupil
Lens offset accounted for	NA	NA	NA	Yes • Accounted for difference in power due to offset	No	Unknown

of the experiments described above did not paralyse the accommodation, and instead relied on the stimulus being presented at or near the far limit of the observers' accommodative range (Dehnert et al., 2011; Ohlendorf et al., 2011; Remón et al., 2014). However, if this distance was incorrect then the observer may have been able to reduce the optical blur by accommodating. Accommodating differently to the rendered stimulus, on the other hand, would not reduce the blur at all as optical defocus can only add to the rendered blur and cannot cancel it out. Remón et al. (2014) presented their stimuli at a distance of 5m, which is 0.2 dioptres (D) from infinity. Similarly, Ohlendorf et al. (2011) presented their stimulus at 4m distance from the observer which is 0.25D from infinity. Dehnert et al. (2011), on the other hand, accounted for the screen distance in the correction of the refractive error of the eye so that (assuming the refractive correction was correct) the screen was actually at the limit of the observer's accommodation. It may be that this explains why there was no significant difference between the two types of blur in the Dehnert et al. (2011) study but there was in both the Ohlendorf et al. (2011) and Remón et al. (2014) studies where the stimulus wasn't quite at infinity, leaving room for some residual accommodation.

2. The human eye also has microfluctuations in accommodation, meaning that the accommodative state is not constant even when the eye is fixated at a single distance. It could be that even if the stimulus is aligned to the average far point of the observer's accommodative range, the microfluctuations in one direction actually reduce the optical blur.

3. In three of the studies described above, the optical blur was introduced by placing a lens in a trial frame worn by the observer. These lenses were between 10mm and 16mm away from the cornea and therefore they were not actually in the pupil plane. This means that the aberrations of the lens would not simply add to the aberrations of the eye. Dehnert et al. (2011) placed the lenses at a distance of 16mm from the cornea and accounted for the difference in lens power due to the lens offset from the pupil plane by slightly altering the power of the actual lens so that the effective power for the eye was correct. For 8D of defocus they actually used a 7D lens and for the 4D condition they used a 3.75D lens. Neither Ohlendorf et al. (2011) or Remón et al. (2014) included an equivalent correction, although they did also have shorter distances between the cornea and the lens of 10mm and 12mm respectively. It is possible that this is one of the factors contributing to the significant effects found in the Ohlendorf et al. (2011) or Remón et al. (2014) studies. Perhaps there was a difference between optical and rendered blur because the optical blur they were introducing was not of the right magnitude due to the offset of the lens from the pupil plane.

4. The separation between the lens and the pupil plane can also cause magnification effects. If this was not accounted for then these magnification effects would affect the retinal image in the optical blur condition but not in the rendered blur condition and therefore may cause some discrepancy between the two conditions. It seems that neither Ohlendorf

et al. (2011), Dehnert et al. (2011), or Remón et al. (2014) accounted for the magnification effects. Ohlendorf et al. (2011) calculated these magnification effects as being less than 5% and concluded that they should not have a significant impact. It therefore seems unlikely that this could account for the significant effects found in the Ohlendorf et al. (2011) and Remón et al. (2014) studies.

5. Most of the studies described above did not account for the longitudinal chromatic aberration (LCA) of the eye so the LCA may have effected the optical blur but not the rendered blur. Because the LCA of the eye increases its depth of field this could help to explain why the VA was better for the optical blur. In fact, one of the differences between the Dehnert et al. (2011) experiment and other similar experiments was that they accounted for the effects of chromatic aberration by using a very narrowband source. It may be because chromatic aberration was not accounted for in other experiments, that there were significant differences between rendered and optical blur. Both Ohlendorf et al. (2011) and Remón et al. (2014) used a broadband light to present all of the stimuli but a monochromatic approximation to generate the PSF for the rendered blur stimuli.

6. The higher order aberrations of the eye also interact with the defocus and astigmatism. It has been shown that these higher order aberrations can increase the depth of focus of the eye (Zhai et al., 2014). Certain aberrations can also help to cancel out other aberrations. For example, it has been shown that when positive spherical aberration is present, the PSF is actually better when there is some positive defocus than when there is no defocus. However, these interactions can only occur with optical defocus. Therefore the higher order aberrations of the eye may interact with the optical defocus and possibly reduce its effect on VA, but the same effect would not be seen for rendered defocus. Ohlendorf et al. (2011) argued that this factor would be too small to explain the magnitude of the difference between the VA for rendered and optical blur found in their study. De Gracia et al. (2009) measured the actual aberrations of the observers' eyes and corrected these optically in the rendered case as well as rendering the images with these aberrations included and still found a significant difference between rendered and

optical blur.

7. As well as the aberrations introduced by the eye, diffraction also has a blurring effect on the retinal image. In the case of the rendered blur, generally this diffraction effect is included in the generation of the PSF or blur disk. However, the blurred image is then viewed through the actual optics of the eye which means that the diffraction effects within the eye further distort the image. It may be that this double effect of diffraction reduces the VA in the rendered case to below that in the optical case. However, this effect would have been similar in the Dehnert et al. (2011), Ohlendorf et al. (2011), and Remón et al. (2014) studies. Therefore, it seems unlikely that this could be the main cause of the difference between the rendered and optical blur in the Ohlendorf et al. (2011) and Remón et al. (2014) studies.

8. The rendered stimuli have to be created for a particular pupil size. Some studies, such as Ohlendorf et al. (2011), used an artificial pupil in order to ensure the pupil size was correct and stayed constant. However, if an artificial pupil is not used then it is possible that the pupil size will vary in the optical condition or not be quite the same as that used to generate the PSF. The larger the pupil size is, the smaller the depth of field is, and the greater effect the defocus and other aberrations have on the retinal image. Dehnert et al. (2011) and Remón et al. (2014) used natural pupils and calculated the PSFs for the measured pupil size. Since Dehnert et al. (2011) did not control for the pupil size and found no significant difference between the two blur types it seems unlikely that this could explain the difference found in the Remón et al. (2014) study.

9. Another possible explanation is that the observers could have been squinting their eyes in the optical condition. This could have a similar effect to reducing the pupil size and therefore increase the depth of field and reduce the impact of the aberrated wavefront on the retinal image. In the Remón et al. (2014) study the participants were specifically instructed not to squint their eyes to try and see the stimuli better. However, even in this cases it cannot be ruled out as a possibility.

10. When the PSFs are generated, various assumptions and approximations must be made. For example, if the PSF is generated using the wave-optics model, Fourier transforms must be taken. Generally this is done using an fft (fast Fourier transform) which is an approximation of a true Fourier transform. The Fraunhofer approximations of diffraction are also inherent in the calculations of the PSFs. It may be that the approximations that go into the generation of the PSF cause the PSF to be inaccurate. However, the Dehnert et al. (2011), De Gracia et al. (2009), Ohlendorf et al. (2011), and Remón et al. (2014) studies all will have relied on these same (or similar) assumptions and therefore it seems that this cannot explain the significant findings of the De Gracia et al. (2009), Ohlendorf et al. (2011), and Remón et al. (2014) studies.

11. Even if the process by which the rendered blur was generated was perfect, there are still limitations as to how accurately the display can present these images. Firstly, the display will only have a limited dynamic range, which may mean that it looses some of the information in the original image. The display may also not be linear. This could mean that some parts of the image are brighter than they should be while other parts are dimmer than they should be. These factors of the display could result in differences between the rendered and optical blur. However, most of the studies described above did correct for the linearity of the displays.

It is worth noting that the fact that Dehnert et al. (2011) did not find any significant difference in VA between the optical and rendered blur does not necessarily mean that the rendered blur was accurate. In fact the two types of blur could still have looked completely different and just happened to have the same effect on VA. In order to ensure that the rendered blur is actually resulting in the same retinal image as the optical blur, a variety of tests using a variety of different stimuli would be needed. The two types of blur may happen to have the same effect on VA for a particular stimulus, but it is possible that this effect would not be robust for different types of stimuli and for different tasks. A subjective test of how similar the different types of blur look would also help to determine whether the rendered blur is equivalent to the optical blur.

6.2 Present Experiment

In this study we have conducted a series of experiments comparing rendered and optical blur for 1D of defocus. We have investigated the impact of various factors including whether an artificial pupil is used, the use of a pinhole in the rendered condition, and the effect of including monochromatic aberrations in the rendering. In addition to the VA tests, we also conducted a subjective similarity test to check that the conditions that were having the most similar effects on va were also subjectively the most similar.

There were three main experiments in this study. The first investigated the effects of artificial pupils, pinholes, and monochromatic aberrations on VA for both rendered and optically blurred stimuli. The second experiment, investigated the effect of rendering with the monochromatic aberrations in more detail. The final experiment was a similarity test to investigate which types of rendered blur were subjectively the most similar to the optical blur.

6.3 General Methods

6.3.1 Participants

A single participant participated in all of the experiments described below. This participant was female and 25 years old. The participant was also one of the experimenters.

6.3.2 Apparatus

A DLP projector (Texus Instruments DLP LightCrafter Display 4710 EVM-G2) was used to present the stimuli to the observer. In order to make the primaries narrower, a short pass filter (Omega Optical 535SP) was placed in front of the green LED within the body of the projector, and a multi bandpass filter (Chroma 69002m) was placed at the output of the projector. Figure 6.1 shows the spectra of the three projector primaries with both filters in place. The projector formed an image on a screen positioned 825mm away, as shown in Figure 6.2.

The projector display was linearised for each of the colour channels separately. Firstly a ThorLabs power meter was used to measure the power of the light emitted by the projector for each primary at every intensity value from 0 to

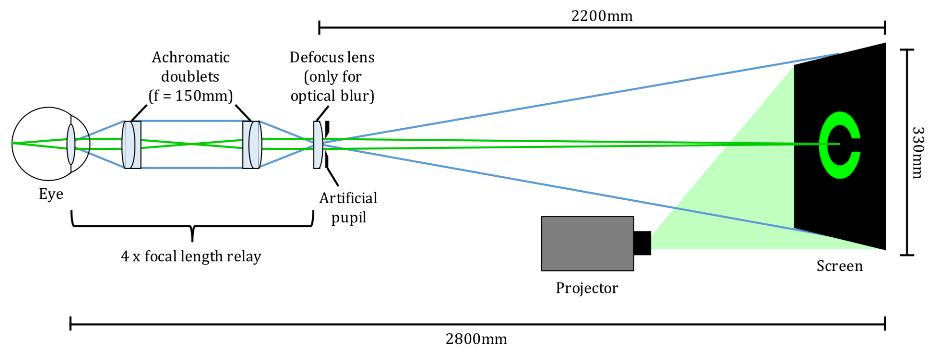

Figure 6.2: A diagram (not to scale) showing the optical layout for the experiments. The projector displayed the stimuli onto a screen at 2800mm from the observer. The observer viewed this screen through a relay lens system composed of 2 achromatic doublets with focal lengths of 150mm each. This resulted in a plane conjugate to the observer's pupil at 2200mm from the screen. In this plane either a defocus lens, or an artificial pupil, or both, could be placed and switched in and out during the course of the experiments using a ThorLabs dual position slider. The green lines indicate the path of the light from a point on the screen and the blue lines highlight the positions of the conjugate planes.

255. At each intensity level the power was calculated as the average of 10 measures. These measured intensities were then used to make a lookup table to linearise the display. Figure 6.3 shows the linearity of the display after the linearisation with the lookup table.

The observer viewed the screen monocularly through a relay lens system. The relay was made up of two achromatic doublets with focal lengths of 150mm. The first was positioned 150mm from the observer's eye and the second was positioned 300mm from the first, resulting in a plane conjugate to the pupil at 600mm from the eye. These lenses were aligned in an interferometer to ensure the spacing was correct. This means there should be no unwanted magnification or defocus term introduced. A ThorLabs dual position slider was mounted in the conjugate pupil plane. A 1D defocusing lens was mounted in one position of the slider and apertures could also be mounted in both positions of the slider depending on the condition. The lens (and any apertures) could then be switched in and out with a command from the computer running the experiment to switch between the optical and rendered blur conditions.

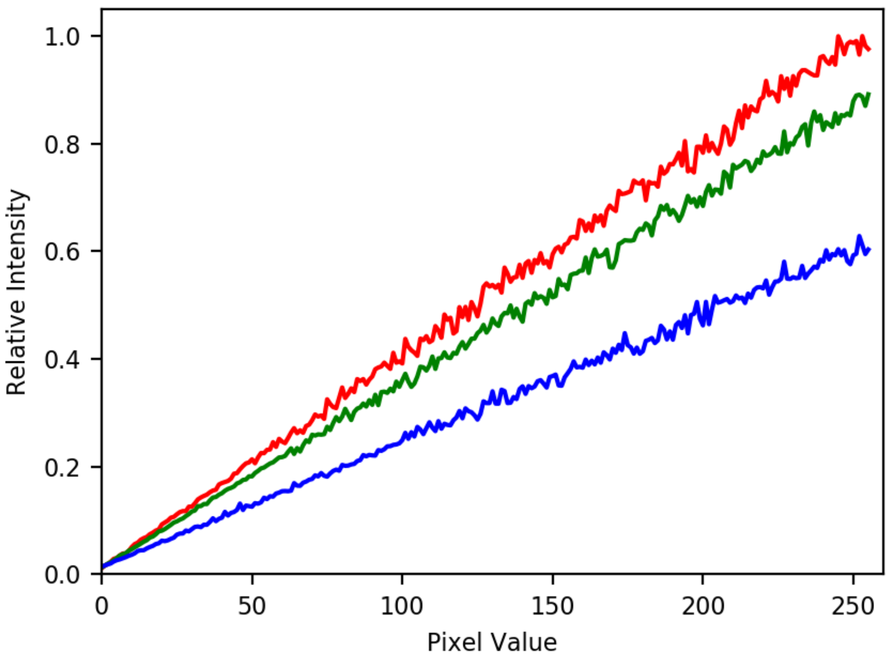

Figure 6.3: The relative measured intensity of the red, green, and blue projector primaries for each input value from 0 to 255 after the linearity correction had been applied. The linearity correction was part of the calibration of the display

Placing the lenses and apertures in the conjugate pupil plane eliminated any magnification effects or changes in power due to lens offset. In cases where an aperture and a lens were used they were placed as close as possible to the pupil plane so any offset was minimal. The set-up of the relay lens system is shown in Figure 6.2.

A chin rest was used to keep the observer's head still. To check that the observer was aligned with the relay lens system, the slider switched between a 1D lens and no lens to ensure the observer could not detect any magnification difference. The observer always viewed the stimulus with her right eye and her left eye was covered with an eye-patch. The conjugate pupil plane was 2200mm from the screen meaning that, without a lens, the screen was at 0.45 D. The observer was slightly myopic and their latest prescription was 0.5 D for their right eye. Therefore, for the rendered case no lens was used and the screen was assumed to be at the far point of the observer's accommodation.

6.3.3 Equating luminance

Some of the conditions involved using a smaller pupil for the rendered case than for the optical case. It was therefore important to ensure that the apparent luminance remained the same across all conditions. A simple scaling factor for the difference in pupil area is not sufficient in this case as it does not take into account the Stiles Crawford effect.

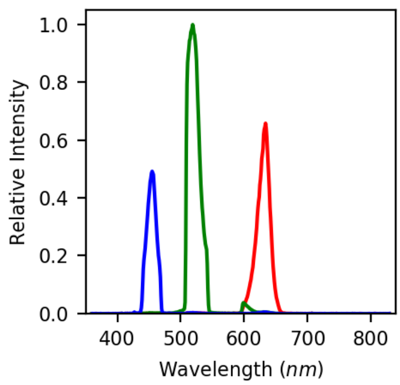

Figure 6.1: The spectra of the red, green, and blue projector primaries after passing through the filters.

A "which is brigher" task was used to determine the exact scaling factor needed for the observer for each pupil size. In this task the observer was shown two stimuli each through a different sized pupil and asked to indicate which was brighter. The two stimuli were generated by illuminating the entire projector screen with the green channel, which, when viewed through the relay lens system, appeared to the observer as a circle of green light. For the larger of the two pupil sizes the intensity of the stimulus was multiplied by the pupil scalling factor.

This task was carried out for a range of possible pupil scaling factors with 20 repetitions of each. This was then repeated for a series of intensity values and for all of the relevant pupil size combinations. In each case, the average response was plotted against the pupil scaling factor. A curve was fitted to this distribution and the 50% threshold of that curve was taken as the optimum correction factor. The correction factors were then averaged across all intensity values. A separate correction factor was used for the different pupil size combinations.

6.3.4 Measuring the wavefront

The observer's wavefront was also measured prior to the experiments. This was done using the custom built wavefront sensor shown in Figure 6.4. An infrared superluminescent diode (SLD) with a peak wavelength of 875nm was used as the light source so that it was barely visible to the observer and the observer would not accommodate to it. This was collimated and stopped down with an aperture before being directed into the eye. This formed a point source at the back of the eye which was then re-imaged by the wavefront sensor. The wavefront sensor used a Shack-Hartmann design with a 20 × 20 lenslet array (aμs: APO-Q-P500-R6.3) and CMOS detector behind. The lenslet array was positioned in a plane conjugate to the pupil. The observer focussed on a stimulus of a red cross presented on a monitor screen while the measurements were taken. A tunable lens (optotune) was also placed in a plane conjugate to the pupil. This was adjusted prior to the wavefront measurement so that the stimulus the observer was accommodating to was at the limit of the observer's

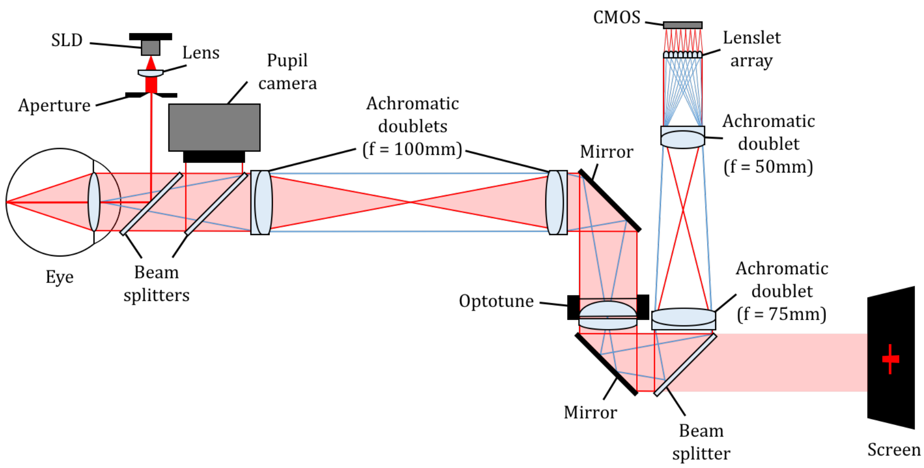

Figure 6.4: A diagram (not to scale) of the wavefront sensor used to measure the aberrations of the observer's eye. The light from the SLD (indicated by the red lines) passed through a collimating lens and an aperture before being directed into the observer's eye with a beam splitter. The light that returned from the eye (still indicated by red lines) was then directed through a relay lens system made up of two achromatic doublets with focal lengths of 100mm. Two mirrors in a perriscope arrangement, then guided the light through an tunable lens (optotune) which was in a plane conjugate to the observer's pupil. The third beam splitter then directed the light from the eye up through a second relay made up of one 75mm focal length lens and one 50mm focal length lens. A Shack-Hartmann wavefront sensor consisting of a lenslet array and a CMOS detector was placed in a second conjugate plane to the pupil. A fixation stimulus was displayed on a monitor screen and the path that the light from the screen took to reach the observer's eye is shown by the pale red shaded region. The blue lines highlight the conjugate planes.

accommodation. The pupil camera show in Figure 6.4 was used to help align the observer prior to the measurement.

A series of at least 50 images were taken with the wavefront sensor. These were then analysed using python to find the best fit of Zernike polynomials up to the 4th order. The averages for each of these Zernike coefficients was taken across all of the images. These average Zernike coefficients were then used to generate the observer's wavefront.

6.4 Experiment 1

The aim of this experiment was to investigate the effects of four factors on the VA for blurred stimuli.

1. The type of blur, which was either optical or rendered.
2. Whether or not an artificial pupil was used. An artificial pupil ensures that the pupil size is constant and that the rendered blur has been calculated for the correct pupil size. However, if the artificial pupil is too different from the pupil plane it may cause artefacts in the retinal image.
3. The aperture size through which the rendered stimulus is viewed. If the rendered stimulus is viewed though a pinhole, then the real aberrations of the eye cannot affect the image optically. This is important as the aberrations would not interact with the rendered defocus as they would with the optical defocus. However, the smaller the pinhole is, the greater the effect of diffraction will be as well.
4. Whether or not the monochromatic aberrations of the eye were included in the rendering of the blur.

We hypothesised that when there was a difference between rendered and optical blur it would be the rendered blur that resulted in a poorer VA. Because the artificial pupil was conjugate (or at least almost conjugate) to the pupil plane, we hypothesised that the rendered and optical blur would be more similar with an artificial pupil than without. We ran some simulations to attempt to find the optimal aperture size in the rendered case. From these it seemed that a 3mm pupil might give the best compromise between diffraction and aberrations and therefore we expected that the rendered and optical blur would be most similar when a 3mm aperture was used in the rendered case. We expected the rendered and optical blur to be least similar when the pupil size was not reduced at all in the rendered case. We expected that including the monochromatic aberrations would improve the rendering and therefore that the rendered and optical blur would be more similar when the monochromatic aberrations were included than when the blur was rendered just for the defocus.

6.4.1 Methods

Design

This experiment investigated four different independent variables. The first was the blur type, which was either optical blur or rendered blur. The second was the pupil type, which was either a 5mm artificial pupil or the observer's natural pupil (i.e. no artificial pupil). The third independent variable was the pupil size through which the rendered stimulus was viewed, and was only applicable when the pupil type was an artificial pupil and when the blur type was rendered. This had three levels, 5mm, 3mm, or 1.5mm. The final independent variable was the higher order aberrations (HOAs). Either the blur was rendered for defocus only, or the rendering also accounted for the observer's measured aberrations.

There were 10 conditions in this experiment. Each was a unique combination of the independent variables described above, as can be seen from Table 6.2. There were 10 repetitions for each of the 10 conditions. The order of the trials was sudo-randomised so that there were 10 sessions, each with 1 trial for each of the 10 conditions. Across the 10 sessions each of the 10 conditions came first once, and each came second once, and so forth.

The dependent variable was the visual acuity (VA). This was measured by altering the stimulus size in a staircase procedure to find the threshold for performance in the task. The VA was calculated as,

$$\mathrm{VA}_{\mathrm{logMAR}} = \log_{10}(\mathrm{gapsize}), \tag{6.1}$$

where $\mathrm{VA}_{\mathrm{logMAR}}$ is the VA expressed as the logarithm of the minimum angle of resolution (LogMAR), and gapsize is the angular size of the smallest detail to be detected, in this case the gap in the Landolt C, in minutes of arc (arcmin).

Stimuli

The stimuli were standard Landolt C stimuli generated in python. These were displayed using only the green channel of the display. The intensity of the C was set to 90% of the maximum and the background was also green at 45% of the maximum. The reason for using a green background was that the projector did not have a spatially uniform black background and had some residual light for the projector primaries. This gave the stimuli a Weber's contrast of 0.99. The orientation of the C was randomised so that on each trial the gap was either on the left, right, top, or bottom.

In the optical blur condition the normal Landolt C was presented with a 1D defocussing lens in the conjugate pupil plane. In the rendered blur condition the Landolt C was first convolved with a PSF. The PSF was generated using the wave-optics model accounting for the pupil size and 1/acd of defocus, or in the HOAs condition, accounting for the pupil size, magnitude of defocus, and other monochromatic aberrations of the eye. Figure 6.5 shows an example of an optical blur stimulus (left), a rendered blur stimulus with no HOAs (middle), and a rendered blur stimulus with the observer's measured aberrations (right).

Table 6.2: Experiment 1 conditions.

<table>
<tr><th rowspan="2"></th><th rowspan="2">Natural pupil</th><th colspan="3">Artificial pupil</th></tr>
<tr><th>5mm optical 5mm rendered</th><th>5mm optical 3mm rendered</th><th>5mm optical 1.5mm rendered</th></tr>
<tr><td>Rendered no HOAs</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>Rendered HOAs</td><td>5</td><td>6</td><td>7</td><td>8</td></tr>
<tr><td>Optical</td><td>9</td><td colspan="3">10</td></tr>
</table>

Procedure

The observer's pupil size was measured prior to the experiments using a Ximea MQ022RG-CM camera. An infrared LED with a peak wavelength of 890nm was used to illuminate the pupil without effecting the pupil size. The observer viewed the experimental stimuli and performed a mini version of the task while their pupil was imaged. The average pupil size of 6.18mm (taken from over 30 images) was used to generate the PSFs for the rendered blur conditions with a natural pupil. The measured pupil size did not drop below 5mm therefore it was never smaller than the artificial pupil.

The task was a 4 alternative forced choice (4afc) task where the observer was asked to indicate the orientation of the Landolt C using the arrow keys on a keyboard. Each stimulus was shown for as long as it took the observer to respond. After the response, the C disappeared and the observer could press the space bar when they were ready for the next stimulus. During this period the observer could also indicate if they had made an error in their response and if they did so that the previous response was discounted.

The thresholds were determined using the accelerated stochastic approximation method or ASA staircase as described in Lu and Dosher (2013). The initial step size for the staircase was set to 0.1 degrees of visual angle and the

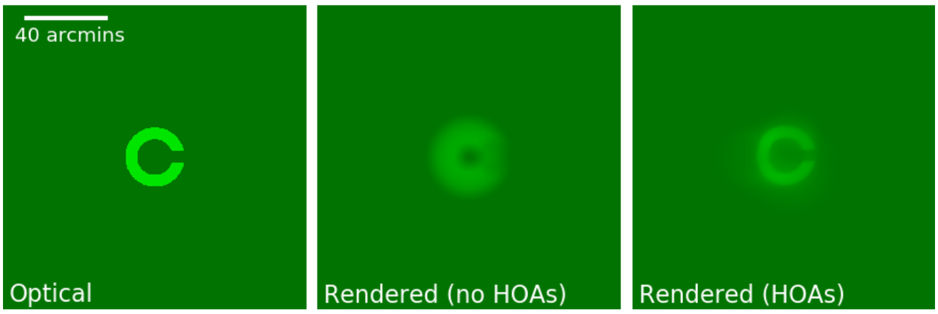

Figure 6.5: Examples of stimuli from Experiment 1. The optical stimulus with no blurring is shown on the left. In the middle is the rendered blur stimulus with a 5mm pupil, 1D of defocus, and no HOAs. On the right is the rendered blur stimulus with a 5mm pupil, 1D of defocus and the observer's higher order aberrations up to the 4th order. The 40 arcmin scale bar applies to all three images. In order for the scale to be accurate the images would need to be viewed from approximately 1 meter.

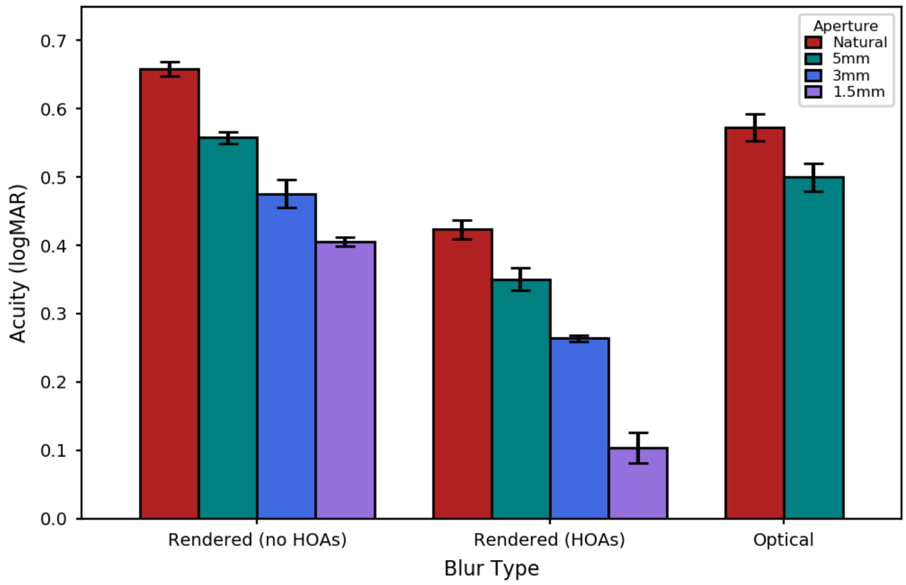

Figure 6.6: The average logMAR values from each of the 10 conditions in Experiment 1. Each bar represents one of the conditions listed in Table 6.2. The error bars show the standard error of the mean.

convergence accuracy level was set to 0.625 (halfway between chance performance and 100% correct). When the observer correctly identified the orientation of the C the stimulus size decreased and when they gave an incorrect response the stimulus size increased. At the end of each staircase the VA estimate was calculated from what the size of the next stimulus would have been.

6.4.2 Results

The average VA values across the 10 repetitions is shown in Figure 6.6. From this graph the general trends are that the VA is better when the blur is rendered with HOAs than when the blur is rendered without HOAs. For each blur type the natural pupil always led to the poorest VA. For the rendered blur, the VA then continued to improve as the pupilsize was reduced with the 1.5mm pupil leading to the best VA. It appears that the VA for the optical blur falls somewhere between those for the various types of rendered blur.

A one-way ANOVA was conducted for all 10 conditions. This showed an overall significant difference in the logMAR VA scores between conditions ($F(9, 90) = 108.78$, $p < .001$). The differences between conditions were then investigated further using Bonferroni corrected t-tests. There were 16 t-tests in total meaning that a result was classed as significant if

$$p \leq \frac{0.05}{16} = 0.0031. \tag{6.2}$$

First we investigated, whether there was a significant difference between rendered and optical blur. We compared each of the rendered conditions with the equivalent optical condition and the difference was found to be significant for six out of the eight rendered conditions. In the conditions without monochromatic aberrations there was a significant difference for the natural pupil (1 vs 9: $t(18) = 3.83$, $p = .001$), with better VA in the optical case ($M = 0.57$, $SD = 0.06$) than in the rendered case ($M = 0.66$, $SD = 0.03$). There was no significant difference between optical and rendered blur with either the 5mm or the 3mm aperture in the rendered condition (2 vs 10: $t(18) = 2.62$, $p = .017$; 3 vs 10: $t(18) = -0.84$, $p = .410$). With the 1.5mm pinhole in the rendered condition, there was a significant difference between the optical and rendered blur (4 vs 10: $t(18) = -4.48$, $p < .001$). However, this time the VA was significantly better for the rendered blur ($M = 0.41$, $SD = 0.02$) than for the optical blur ($M = 0.50$, $SD = 0.06$). In the conditions with HOAs there was always a significant difference between the optical and rendered blur (5 vs 9: $t(18) = -6.14$, $p < .001$; 6 vs 10: $t(18) = -5.74$, $p < .001$; 7 vs 10: $t(18) = -11.37$, $p < .001$; 8 vs 10: $t(18) = -13.18$, $p < .001$). In every case with HOAs the blur rendered with monochromatic aberrations lead to a better VA than the optical blur.

Secondly we tested whether the use of a smaller physical aperture size in the rendered condition (while rendering the blur for the same optical pupil size of 5mm) had a significant impact on the VA. We conducted 4 t-tests comparing the conditions with the 5mm aperture in the rendered condition with the 3mm and the 1.5mm aperture rendered conditions for both the no HOA and the HOA rendering methods. All of these t-tests showed significant results (2 vs 3: $t(18) = 3.69$, $p = .002$; 2 vs 4: $t(18) = 14.22$, $p < .001$; 6 vs 7: $t(18) = 5.07$, $p < .001$; 6 vs 8: $t(18) = 8.93$, $p < .001$) with the smaller aperture size resulting in a better VA in every case.

Finally the effect of including HOAs when generating the PSF for the rendered blur condition was investigated. This was done by comparing each of the 4 conditions rendered without HOAs with their equivalent conditions rendered with HOAs. In all cases there was a significant difference in the VA (1 vs 5: $t(18) = 13.81$, $p < .001$; 2 vs 6: $t(18) = 11.15$, $p < .001$; 3 vs 7: $t(18) = 10.10$, $p < .001$; 4 vs 8: $t(18) = 13.07$, $p < .001$) with the VA being better in the conditions with HOAs than without HOAs in every case.

6.4.3 Discussion

Only two of the rendered conditions showed no significant difference from the equivalent optical condition. These were conditions 2 and 3, neither of which included HOAs in the rendering and both used an artificial pupil. For condition 2 the aperture size in the rendered case was 5mm (the same as the optical pupil size that the blur was generated for) and for condition 3 the aperture size in the rendered case was 3mm. However, just because these two cases were the ones where the VA was not significantly different from the optical case, this does not mean that these two cases resulted in the most accurate retinal images.

One unexpected finding was that in most of the cases where there was a significant difference between optical and rendered blur, it was in fact the rendered blur that led to the better image quality. As was discussed in the introduction, in similar previous studies, when a significant difference was found between the VA for rendered and optical blur it was always the case that people were more tolerant to optical blur. This suggests that in this case there is actually something in the optical case making the image quality worse that we are missing from the rendered case.

From the results it is clear that there are various factors that reduce the image quality of the VA and various factors that improve it. For example, it is to be expected that (once the pupil is large enough that diffraction does not have a dramatic effect on the retinal image) a larger pupil size should result in a greater impact of aberrations and therefore a poorer image quality. It is unsurprising, therefore, that there is a trend for the VA to be better with the artificial pupil than with the natural pupil in both the rendered and optical cases because the artificial pupil is smaller than the natural pupil. There is also a significant effect that as the rendered aperture size is reduced the VA improves. Although in these cases the PSFs are always generated for a 5mm pupil, the images are still affected by the real aberrations of the eye when they are viewed and therefore the VA still improved as the artificial pupil was stopped down. This finding actually suggests that as the VA was best for the 1.5mm pupil, there must have been less distortion to the retinal image from the optics of the eye for the 1.5mm pinhole than for the 3mm and 5mm pupil and therefore that the image would have been be more similar to the stimulus being presented. Because the image being presented was essentially generated as what the retinal image should look like, the less distortion there is from the real optics of the eye when it is viewed the better. Therefore, these findings suggest that the best way to present a rendered blur stimulus to the observer is through a 1.5mm pupil, as opposed to a 3mm or 5mm pupil.

Another finding was that the VA was significantly better in the cases where the rendering included HOAs than when the rendering was for defocus alone. This could be because although the HOAs reduce the image quality for an in focus object, they also increase the depth of focus making us more tolerent to defocus and increasing the image quality for out of focus objects.

The stopping down of the pupil size for presenting the rendered stimuli and the inclusion of HOAs in the generation of the PSF for the rendered blur should both bring the retinal image in the rendered blur case closer to that for the optical blur. However, in this experiment both of these factors actually seemed to increase the difference in VA when compared with the equivalent optical blur condition. For every one of the rendered HOA conditions the VA was significantly better than in the equivalent optical condition and for both of the conditions with the 1.5mm pinhole the VA was also significantly better than in the equivalent optical condition. In fact the only cases where there was no significant difference was when the HOAs weren't taken into account for the 5mm and 3mm aperture sizes. We would expect these conditions to lead to a relatively poor approximation of the optical blur. There must, therefore, be another explanation as to why the conditions that we would have expected to give the best approximation of the optical blur lead to a significantly better VA.

There are two explanations which, when combined, could explain this pattern of results. The first is that perhaps rather than the stimulus being presented at the limit of the observers accommodation (infinity for a corrected eye), it was in fact presented beyond this point, meaning that the eye would need to accommodate beyond its limit to bring the stimulus into focus. If this was the case then as well as the desired rendered or optical defocus there would be an additional optical defocus term. This additional optical defocus term would affect the optical and rendered cases differently because optical + optical defocus is different from optical + rendered defocus. However, at least for the rendered cases with the same pupil size as the optical conditions (i.e. the natural pupil or the 5mm pupil) the magnitude of this defocus should be the same and the effect on the retinal image should not be too different from in the optical condition. In the conditions where the pupil was stopped down to present the rendered stimulus, this additional optical defocus would have a lower magnitude due to the smaller pupil size and therefore would degrade the resultant retinal image less. If this was the case then this would account for the significantly improved VA in the rendered conditions with the stopped down pupil.

The rendered blur with HOAs also led to a significant improvement in the VA compared to the equivalent optical case. This was the case not only with the stopped down pupil sizes but even for the natural and 5mm pupil and therefore this unexpected finding cannot be explained purely by the unintentional defocus offset suggested above. To render the defocus blur with the HOAs included the defocus term was kept the same as it was in the normal rendered case. However, this is not actually appropriate. Defocus interacts with the other aberrations of the eye and therefore in an eye with HOAs the defocus term required to bring an object into best focus is not necessarily 0D, in fact it generally isn't. One example of an aberration that interacts with defocus in this way is spherical aberration. In an eye with positive spherical aberration, the best image quality is actually obtained with some positive defocus to balance out the spherical aberration. Therefore, when simulating an in focus retinal image for an eye with HOAs the defocus term should not be zero but should instead be that which best balances out the HOAs of the eye. It follows that to simulate the retinal image for an out of focus eye with HOAs the desired defocus should be added to the defocus value which best balances out the other aberrations.

6.5 Experiment 2

The aim of this experiment was to further investigate the effects of rendering blur with and without accounting for the HOAs while correcting the potential issues in Experiment 1.

The first potential issue with Experiment 1 was that the stimulus may not have been presented at the far limit of the observer's accommodation. Due to the experimental setup we were not able to adjust the actual distance of the screen. Therefore, in order to account for the potential offset, the experiment was run both with the green primary (as in Experiment 1) and with the red primary. The eye is less myopic for red light than for green light due to LCA and in this case the separation between the red and the green primaries was approximately 0.5D. If the green stimulus was beyond the accommodative range by approximately 0.5D or less, then the red stimulus should be just within the accommodative range.

The second potential issue with Experiment 1 was that the defocus term used in the simulation was the same as the defocussing power of the lens. However, in an eye with monochromatic aberrations the position of best focus is often not actually 0D defocus. In this experiment the optimal focus, or baseline defocus, was first established for the given aberrations using a simulation. The induced defocus was then added to this baseline defocus to give the defocus value used to generate the PSF.

This experiment was also designed to investigate whether the HOAs used in the rendering need to be the observer's own. This is because in many situations when rendered blur is used the observer's HOAs will not be known or the same stimuli will be presented to multiple observers and therefore cannot be personalised. It would therefore be useful to know if including HOAs generally improves the similarity of the rendered blur with the optical blur even when the HOAs are not the specific HOAs of the observer.

6.5.1 Methods

Design

This experiment had one independent variable, which was the type of blur. There were 4 different conditions corresponding to 4 different types of blur. These were optical blur, rendered blur, rendered blur with HOAs, and rendered blur with other HOAs. The conditions and their corresponding numbers are shown in Table 6.3. In the final condition the PSF was still generated for an eye with HOAs but they were actually the HOAs of another observer measured using the same wavefront sensor. This other participant was male and

29 years old.

There were 10 repetitions for each of the 4 conditions. The order of the trials was sudo-randomised so that there were 10 sessions each with 1 trial for each of the 4 conditions. Across the 10 sessions each of the 4 conditions came first at least twice, and each came second at least twice, and so forth.

Table 6.3: Experiment 2 conditions.

Type of Blur	Number
Optical	1
Rendered no HOAs	2
Rendered HOAs	3
Rendered other HOAs	4

The dependent variable was the VA. As in Experiment 1 this was determined using an ASA staircase and converted to logMAR using equation 6.1.

The experiment was carried out three times. The first time was with the green primary and with a 5mm pupil used in the optical case and a 1.5mm pinhole used in the rendered case. The second time was with the red primary and with a 5mm pupil used in the optical case and a 1.5mm pinhole used in the rendered case. The final time was with the red primary but with a 5mm pupil used in both the optical and the rendered case.

Baseline Defocus Simulation

A simulation was carried out for each set of HOAs to determine the defocus value which best balanced out the aberrations. In this simulation the PSFs were generated for the given aberrations and a series of different defocus values in steps of 0.01D. For each of these PSFs the Strehl ratio was calculated using equation 5.1. The baseline defocus for that wavefront was then taken as the defocus value that resulted in the highest Strehl ratio. The simulated Strehl ratios and baseline defocus values for each set of aberration is shown in Figure 6.7.

Stimuli

The stimuli were standard Landolt C stimuli generated in python as described for Experiment 1. The only difference here was that for 2 of the experiments the stimuli were rendered for and displayed using the red primary rather than the green.

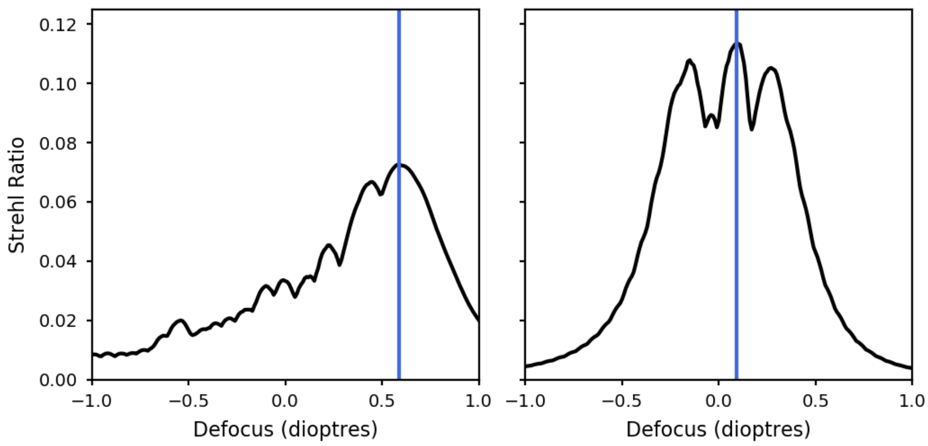

Figure 6.7: The calculated Strehl ratios across a range of defocus values for the observer's own aberrations (left) and the aberrations measured from the other participant (right). The Strehl ratios were calculated assuming a 5mm pupil and a wavelength corresponding to the peak wavelength of the green projector primary. The blue lines indicate the defocus value corresponding to the optimum Strehl ratio. The value indicated by this blue line was taken as the baseline defocus.

As in Experiment 1, in the rendered blur conditions the Landolt C was convolved with a PSF. In the case with no aberrations, the PSF was generated for the 5mm pupil size and 1D of defocus. However for the HOA conditions the PSF was generated for the measured HOAs with 1D of defocus plus the baseline defocus for those aberrations. Figure 6.8 shows and example of a rendered blur stimulus with no monochromatic aberrations (left), a rendered blur stimulus with the observer's measured aberrations (middle), and a rendered blur stimulus with the other participant's measured aberrations (right).

Procedure

The task was the same 4afc task as described for Experiment 1 above and the thresholds were determined using the same ASA staircase. At the end of each staircase the VA estimate was calculated from what the size of the next stimulus would have been.

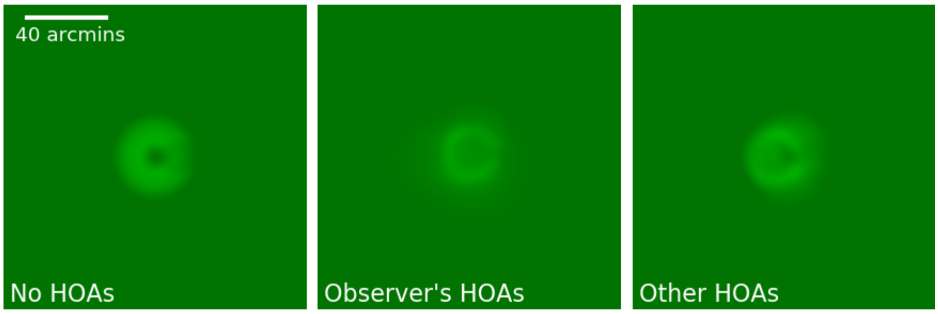

Figure 6.8: Examples of stimuli from Experiment 2. On the left is the rendered blur stimulus with 1D of defocus and no HOAs. In the middle is the rendered blur stimulus with the observer's higher order aberrations up to the 4th order and 1D of defocus plus the baseline defocus to best compliment those aberrations. On the right is the rendered blur stimulus with another participant's higher order aberrations up to the 4th order and 1D of defocus plus the baseline defocus to best compliment those aberrations. The 40 arcmin scale bar applies to all three images. In order for the scale to be accurate the images would need to be viewed from approximately 1 meter.

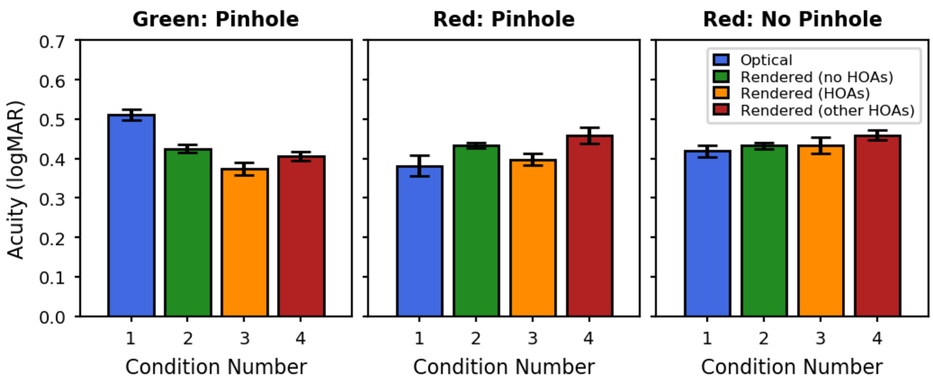

Figure 6.9: The average logMAR values for the 4 blur conditions. The top graph is for the green stimulus with a 1.5mm pupil to present the rendered blur stimuli. The middle graph is for the equivalent condition with the red stimulus. The bottom graph is for the red stimulus with both the optical and rendered blur stimuli presented through the 5mm pupil. The error bars show the standard error.

6.5.2 Results

The first stage of the experiment involved displaying the stimuli with the green primary of the projector and displaying the optical stimuli through a 5mm artificial pupil, and the rendered stimuli through a 1.5mm pinhole. The average logMAR scores for each of the 4 conditions can be seen in the top panel of Figure 6.9. This shows that the VA is worst in the optical blur condition (1). Out of the rendered blur conditions, the VA was best when the rendering included the observer's own aberrations (3), and was worst when the rendering did not include any HOAs (2).

An ANOVA showed there to be a significant effect of the type of blur on VA for this first stage of the experiment ($F(3, 36) = 20.13$, $p < .001$). Bonferroni corrected t-tests were then carried out on all 6 possible combinations of conditions to evaluate this effect. With the Bonferroni correction a t-test was classed as significant if

$$p \leq \frac{0.05}{6} = 0.0083. \tag{6.3}$$

The t-tests showed that all three of the rendered blur conditions were significantly different from the optical blur condition (1 vs 2: $t(18) = 5.06$, $p < .001$, 1 vs 3: $t(18) = 6.43$, $p < .001$, 1 vs 4: $t(18) = 6.13$, $p < .001$). In every case the VA was significantly better in the rendered condition than the optical condition.

The t-tests showed no significant differences between any of the different rendered blur conditions (2 vs 3: $t(18) = 2.59$, $p = .019$; 2 vs 4: $t(18) = 1.27$, $p = .219$; 3 vs 4: $t(18) = -1.60$, $p = .127$).

The second stage of the experiment also involved displaying the optical stimuli through a 5mm artificial pupil and the rendered stimuli through a 1.5mm pinhole, but this time the stimuli were displayed with the red primary. The average logMAR values from this part of the experiment are shown in the middle panel of Figure 6.9. Here, optical blur condition (1) seems to have the best VA and the rendered blur condition with the HOA's from another participant (4) seems to have the worst VA.

The Levenes test for the second part of the experiment showed that the variances varied significantly between conditions ($F(3, 36) = 3.04$, $p = .041$) and although there seemed to be an overall significant effect with the standard

ANOVA ($F(3, 36) = 3.47$, $p = .026$) there was not a significant effect with the Welch ANOVA ($F(3, 18.16) = 3.14$, $p = .051$). To be certain we also ran Bonferroni corrected t-tests for each of possible combinations of conditions and none of these came out as significant.

The third stage of the experiment also used the red primary but this time a 5mm artificial pupil was used to present both the optical and the rendered stimuli. The average logMAR values for this part of the experiment are shown in the bottom panel of Figure 6.9. The VA in all four conditions is very similar with the best performance in the optical blur condition (1) and the worst performance in the rendered blur condition with the HOAs from another observer (4). Here an ANOVA showed no significant difference between any of the conditions ($F(3, 36) = 1.35$, $p = .274$).

6.5.3 Discussion

As was found in Experiment 1, when the green primary was used, with the 1.5mm pinhole to present the rendered stimuli, the rendered blur always resulted in significantly better image quality than the optical blur. This was the case regardless of whether or not HOAs were included in the rendering and whether the HOAs were the observer's own.

Unlike in Experiment 1 were no significant differences found between any of the rendered blur conditions. This may be because this time the baseline defocus was included for the HOAs conditions so that the level of blur was more similar to that in the rendered condition with no HOAs. This suggests that the main reason for the dramatic difference between the rendered condition with no HOAs and the rendered condition with HOAs in Experiment 1 was that the baseline defocus was not accounted for.

When the red primary was used instead, there was no significant difference between the optical and rendered blur. This was true regardless of whether or not HOAs were included in the generation of the rendered blur and regardless of whether or not a pinhole was used to present the rendered blur. In Experiment 1 using a pinhole for the rendering had a dramatic effect on the VA. The findings from this experiment support the idea that the reason for this dramatic difference in Experiment 1 was that there was some additional optical defocus for both the optical and rendered conditions resulting from the stimulus being placed beyond the far limit of the observer's accommodative range. Therefore, stopping down the pupil was not just lessening the effects of the observer's HOAs but also lessening the effects of this defocus. Using the red primary had the equivalent effect to bringing the stimulus 0.5D closer to the observer and it seems that this was sufficient to eliminate this additional defocus.

These findings seem to suggest that it does not really matter whether or not the HOAs are included in the rendering and whether a pinhole is used to present the rendering because none of these factors significantly change the resultant VA. In fact, when the red primary was used the VA was not significantly different for the optical vs rendered blur regardless of whether the rendered blur included HOAs, whether the HOAs were those measured from the observer, and whether a pinhole was used. However it is important to remember when interpreting these findings that even if these different conditions do have a very similar effect on VA this does not mean that they are qualitatively the same and they may in fact still appear very different to the observer.

6.6 Experiment 3

In this final experiment, instead of investigating the effects of various types of blur on VA we investigated which type of rendered blur looked qualitatively most similar to the optical blur. We hypothesised that the rendered blur with HOAs would be judged as most similar to the optical blur and that the rendered blur with no HOAs would be the least similar to the optical blur.

6.6.1 Methods

Design

There were two independent variables in this experiment. The first was the types of rendered blur being compared. The types of rendered blur were the same as those used in Experiment 2 and every possible pairing was tested. Therefore, this first variable had three levels: no HOAs vs HOAs, no HOAs vs other HOAs, and HOAs vs other HOAs. The second independent variable was the diameter of the stimulus. This had 4 levels 0.3, 0.5, 0.7, and 0.9 degrees of visual angle. This made 12 different conditions in total.

There were 20 repetitions for each condition. The order of presentation for the two types of rendered blur was counterbalanced so of the 20 repetitions, 10 were for one order of presentation and 10 for the opposite order. In each session there were 24 trials: one for each of the two orders of presentation for each of the 12 conditions. The order of these trials was randomised for each session.

The dependent variable was the type of rendered blur chosen as appearing most similar to the optical blur.

Stimuli

The stimuli were standard Landolt C stimuli generated in python exactly as described for the Experiment 2. However, for this experiment the stimuli were only presented with the green primary and the 1.5mm pinhole was used to view all of the rendered blur stimuli. As in Experiment 2 there were 3 types of rendered blur stimuli: those rendered with no HOAs, those rendered with the observers own HOAs, and those rendered with another participant's HOAs. As with Experiment 2 the baseline defocus values were added to the desired defocus value of 1D when HOAs were included in the rendering.

Procedure

For each trial three stimuli were shown. The first stimulus was always the optically blurred stimulus. This was presented with a 5mm artificial pupil. This was displayed for 0.5s followed by a black screen for 0.5s. While the black screen was presented the 1D lens and 5mm artificial pupil were exchanged with a 1.5mm pinhole using the dual position slider. Next the first of the rendered blur stimuli was shown for another 0.5s followed by another black screen for 0.5s. Finally the second rendered blur stimulus was shown for 0.5s followed by a black screen. At this point the subject was able to indicate which, out of the two rendered stimuli, looked most similar to the first, optical blur stimulus by pressing either the number 1 (for the first rendered stimulus) or 2 (for the second rendered stimulus) on the keyboard.

6.6.2 Results

The frequency with which each type of rendered blur was selected as being closest to the optical blur for each of the 3 comparisons is shown in Figure

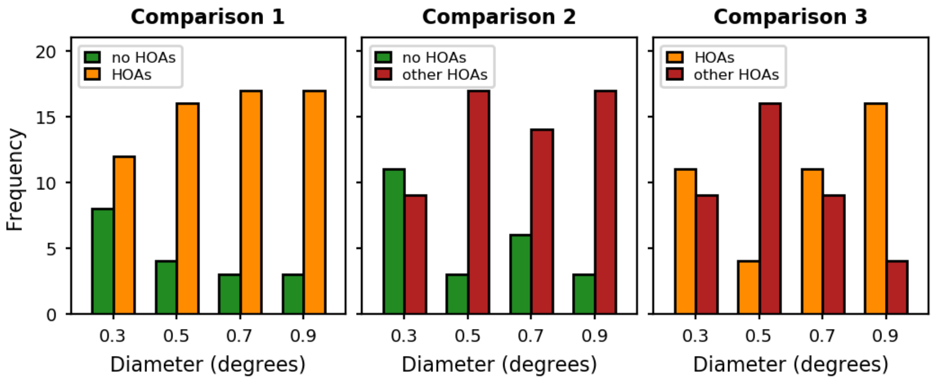

Figure 6.10: The frequencies with which the observer selected each rendered blur condition as closer to the optical blur stimulus for each of the three comparisons. The results are plotted for each of the 4 stimulus diameters tested.

6.10. For the comparison of the no HOAs condition with the observer's HOAs condition (top panel), the observer's HOAs condition was chosen as being more similar to the optical blur with a higher frequency for every stimulus size. For the comparison of the no HOAs condition with the other HOAs condition (middle panel), the other HOAs condition was selected with a higher frequency for 3 out of the 4 stimulus sizes. For the final comparison of the observer's HOAs against the other HOAs condition (bottom panel), the results seem to be a lot more mixed.

A chi-squared test was carried out for each of the comparisons to determine whether there was a significant difference in the frequencies for the two blur types. A chi-squared test of independence was also carried out for each of the three comparisons to establish whether stimulus diameter had a significant effect on the result.

There was a significant difference between the frequencies for the no HOAs versus HOAs comparison (X^2 $(1, N = 80) = 24.20$, $p < .001$), with the HOAs condition being selected significantly more times (62) than the no HOAs condition (18). The frequency with which each of these conditions was selected did not differ significantly with the stimulus diameter (X^2 $(3, N = 80) = 4.87$, $p = .246$).

There was also a significant difference between the frequencies for the no HOAs versus other HOAs comparison (X^2 (1, N = 80) = 14.45, $p < .001$), with the other HOAs condition selected significantly more times (57) than the no HOAs condition (23). For this comparison there was a significant interaction between the type of rendered blur selected and the stimulus diameter (X^2 (3, N = 80) = 10.43, p = .018). To investigate this interaction further, individual chi-squared tests were run for each of the 4 stimulus diameters. There was a significant difference between the no HOAs and the other HOAs frequencies for both the 0.5^o stimulus (X^2 (1, N = 20) = 9.80, p = .003) and the 0.9^o stimulus (X^2 (1, N = 20) = 9.80, p = .003) with the higher frequency for the other HOAs condition in both cases. However, the difference was not significant for the 0.3^o stimulus (X^2 (1, N = 20) = 0.20, p = .824), or for the 0.7^o stimulus (X^2 (1, N = 20) = 3.20, p = .115).

There was no significant difference between the frequencies for the HOAs versus other HOAs comparison (X^2 (1, N = 80) = 0.20, p = .738). Although the frequency was slightly higher for the HOAs condition (42) than the other HOAs condition (38). There was, however, a significant interaction with stimulus diameter (X^2 (3, N = 80) = 14.64, p = .002). To investigate this interaction further, individual chi-squared tests were run for each of the 4 stimulus diameters. There was a significant difference found for the 0.5^o stimulus (X^2 (1, N = 20) = 7.20, p = .012), with a higher frequency in the other HOAs case (16) than the HOAs case (16). There was also a significant difference found for the 0.9^o stimulus (X^2 (1, N = 20) = 7.20, p = .012). However, in this case the frequency was higher for the HOAs condition (16) than the other HOAs case (4). There was no significant difference found for either the 0.3^o stimulus (X^2 (1, N = 20) = 0.20, p = .824) or the 0.7^o stimulus (X^2 (1, N = 20) = 0.20, p = .824).

Figure 6.11 shows the overall frequencies for each of the three types of rendered blur. From this we can see that the no HOAs condition was selected dramatically fewer times than either of the HOAs conditions. The HOAs condition was also selected slightly more than the other HOAs condition.

6.6.3 Discussion

The results of Experiment 3 show clearly that the observer judged the HOAs condition to be to more similar to the optical blur than the no HOAs condition. This finding was significant and robust regardless of the stimulus size. These findings therefore indicate that rendering with HOAs leads to a more realistic image.

Another interesting question is whether it is important that the aberrations used in the rendering are the observer's own aberrations. In this experiment, the observer also judged the other HOAs condition to be more similar to the optical blur than the rendered blur with no HOAs. This was also significant and it was only at the smallest stimulus size that this trend was not seen. This indicates that even in cases when the aberrations used are from another observer this can still make the image appear more realistic. In fact, there was no overall significant difference between the frequencies with which the HOAs condition was chosen and the other HOAs condition was chosen, indicating that the important factor in making the rendered stimuli appear more similar to the optical stimuli was that HOAs were included and it didn't actually make much of a difference whether these aberrations were the observer's own or not.

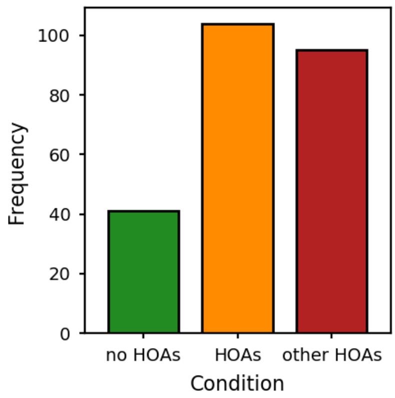

Figure 6.11: The overall number of times that each of the three types of stimuli were selected as being closer to the optical blur stimulus across all of the trials.

More experiments are required testing a range of observers with a range of aberrations to determine whether this effect is robust. It is also worth noting that in this experiment only the green primary was used, when the results of Experiment 2 actually indicate that when the green primary is used the stimulus is beyond the limit of the observer's accommodation so the optical defocus would have been a higher value than anticipated. This effect would have influenced all three types of rendered blur in the same way though and therefore the comparisons made between the different types of rendered blur should still be valid.

If these finding are robust, this suggests that HOAs could be used in the rendering of blur even when the stimuli are presented to multiple different people at once or when the specific aberrations of the observer are not known and it would still be effective in making the images appear more realistic.

6.7 Conclusions

Experiments 1 and 2 indicated that if the distance at which the stimulus is presented is not actually the far point of the observer's accommodative range this can alter the results quite dramatically and lead to significant effects which, when the effective distance is changed slightly, disappear.

They also demonstrated the importance of finding a baseline defocus value when rendering with HOAs and adding the desired defocus term to this baseline defocus. It is well established that the point of best focus for a real eye with HOAs is not actually at 0 defocus, and this is a good example of a practical case where this needs to be accounted for.

Once these two factors above were corrected for in Experiment 2, by using the red primary to effectively bring the stimulus closer to the observer and adding the defocus to a baseline level in the HOA conditions, there was actually no significant difference found between the VA for optical and rendered blur. This was the case regardless of whether or not the rendered stimuli were presented through a pinhole and regardless of whether HOAs were included in the rendering. It was even the case when the HOAs used in the rendering were measured from another participant's eye. It may seem sensible to conclude from this that it does not really matter whether or not HOAs are included and whether or not the rendered stimuli are viewed through a pinhole. However, just because there was not a significant difference in the VA, this does not mean that there was no significant difference in how realistic the stimuli were.

Experiment 3 actually indicated that there was a significant difference in how similar to the optical blur the different types of rendered blur appeared. When the rendered blur included HOAs this was chosen significantly more frequently as being closer to the optical blur compared with when the stimulus had no HOAs. This was true regardless of whether or not the HOAs used to render the blur were the observer's own. There was however, no overall significant difference between the frequencies with which the observer selected the two different HOAs condition. This seems to indicate that whether the aberrations are the observer's own does not make a significant difference to how similar the rendered stimulus looks to the optical stimulus. However, the observer did still select the stimulus with their own aberrations slightly more than the stimulus with someone else's aberrations.

Overall these results suggest that, at least for the two eyes measured in this experiment, the HOAs of the eye don't significantly alter the VA for Landolt C stimuli. However, the images blurred with HOAs are qualitatively different from those blurred without HOAs and the observer judged those blurred with HOAs as more closely resembling the real optically blurred stimuli. This suggests that, in cases where the aim of the rendered blur is to make a stimulus appear qualitatively to be as realistic as possible, HOAs may well be important. This also shows that there is a lot that a simple comparison of VA will not tell us about how accurate a stimulus with rendered blur is.

Following on from this more experiments are needed testing a greater number of observer's to establish how robust these effects are. A range of different HOAs could also be tested to see whether there is a particular set of HOAs (such as the HOAs for a "standard" observer) which can improve the realism of rendered blur above that for rendered blur with no HOAs for the majority of the population.