Determination of the Optimal Aperture Size of a Pinhole Camera by Measuring Image Clarity

By

Dania Allgood
Marion Asang
Kyle Carroll
Treavor Ellington
Kaye Peden
Tiffani Perez

Ben Perkins
Cheyenne Simmons
Lili Tha
Isaiah Thomas
Devin Tingle

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Judy Ninesteel
Deirdre Robertson
Daniel Beatty
Samantha Crabtree
INTRODUCTION

Light comes from sources that emit light energy, and it travels in straight lines in all directions. When light is blocked by an object a dark area is created behind it: a shadow, or absence of light. Diffraction is the bending of light around an object which causes shadows to form with blurry edges (Johnston, 2006) (Fig. 1).

![Diffraction's effect on a shadow.](image)

Fig. 1. – Diffraction’s effect on a shadow.

Light is also reflected off of objects illuminating objects and making them visible to human eyes. When the light reflects, it travels in all directions just as it does when travelling from its source (Fig. 2). In this study, we investigated what happens when a hole is placed in light’s path.

![Light rays reflecting off an object in all directions.](image)

Fig. 2.- Light rays reflecting off an object in all directions.

If a small hole, like a pinhole, is placed in the path of the light, some of the rays pass through that hole, causing the objects image to appear on a screen on the other side of the hole (fig. 3). Applying this small hole to an object creates a pinhole viewer. The light rays that don’t pass through the hole are either absorbed or reflected by the wall. When light passes through the hole, the image is inverted on both the x and y axis. This inversion happens because light travels in straight lines; the rays from the top of an image appear on the bottom of the screen, as it will from the bottom of the image and the sides (fig. 3). If light entering the pinhole is from a direct source, instead of reflected light, then any object blocking it appears as a shadow on the screen. (Plesser & Heffernan, n.d.)
As seen in Figure 4, the trees are shadows and the car and person are images created by reflected light. Using these properties, pinhole viewers show both shadows and images; pinhole cameras use similar properties.

A pinhole camera captures light on film or photographic paper. The image produced is affected by the amount of light reaching the paper, which is controlled by the aperture size (pinhole size) and exposure time. As the aperture gets smaller less light enters the hole and more exposure time is required for the image to develop.

The aperture size also influences the sharpness of the image. With a large aperture size, the image is unclear because too many light rays from each point reach the paper, spreading the image and causing blurring. A smaller aperture size increases the sharpness of an image by "restricting the light rays coming from the subject to a confined region" (Emmel, 2001), decreasing the spread of light and making a clearer image (Fig. 5) (Emmel, 2001).
One of the benefits of a smaller aperture is the increased sharpness; however if the hole is too small, diffraction becomes noticeable and the image begins to blur. Light has wave properties, allowing it to bend when necessary (Fig. 6). When waves encounter a small opening they bend around the edges as demonstrated in Figure 6. When waves interfere with one another, as shown in Figure 6, they create an interference pattern where some of the waves are amplified and others are canceled (Johnston, 2006).

When waves pass through a circular opening and bend a circular interference pattern is created, as shown in Figure 7. This pattern is referred to as an airy disc interference pattern. As the aperture approaches the size of the airy disc interference pattern, the interference causes the image to appear blurred.
Fig. 7. – This figure shows the interference pattern known as the Airy Disc.

Formulas have been developed to predict an aperture size where diffraction decreases image clarity. These formulas use the focal length of the camera, the wave length of light used, and a constant, to find a diameter that produces the sharpest image before diffraction becomes noticeable (Johnston, 2006) (Plesser & Heffernan).

The purpose of our study was to determine the optimal aperture size for a pinhole camera that created the clearest and sharpest image before diffraction became noticeable. We used the formula \( d = \sqrt{C\lambda f} \), where \( d \) is the diameter of the pinhole size, \( C \) is the constant for the formula, \( \lambda \) is the wavelength, and \( f \) is the focal length. The apertures available were of sizes between 400\( \mu \)m (microns) and 200\( \mu \)m in increments of 50\( \mu \)m. Using the median aperture size, of 300\( \mu \)m, and the average wavelength of our light source of 536.66 nm, we found the focal length of the pinhole camera to be 67.5 mm. In our study, we surveyed participants to determine the image with the best clarity and sharpness. Our hypothesis is: If a pinhole camera has a focal length of 67.5 mm, then the optimal pinhole size, based on image clarity, will be the 300 micron aperture size.

METHODS

Our study was conducted in a small room where three stations were set up for photography. The room had black walls and a black ceiling to prevent reflection of light during the exposure process. On the walls at each station was an image with several black-and-white spirals for the camera to replicate on photographic paper. Each station also had a 100 watt halogen lamp, clamped to a ring stand 63.9 cm from the wall and 76.5 cm above the table. In front of the light, the camera was placed 21.3 cm from the wall and 34.5 cm high to allow it to fully capture the image (Fig. 8).
Fig. 8. – The set up for capturing our images.

We used a container, with a focal length of 6.75cm, for our camera, and spray-painted it black to prevent light from entering (Fig 9). We carved a dime sized hole in its center, to allow the placement of the appropriate aperture. The apertures were all laser-cut holes made by the Lenox laser company ranging from sizes 200μm – 400μm in increments of 50. The shutter on the front of the camera was made of black construction paper, to prevent light from entering the camera; and blue painters tape, for security and easy removal of the shutter during the exposure process.

Fig. 9. – A picture of our pinhole camera.

We used Resin-Coated black and white photographic paper to capture images of spirals. We calculated each exposure time by using an online website guide (Pinhole Camera Exposure Guide , n.d.) For each of the five aperture sizes, we used a specific exposure time when capturing an image (Table 1). Then, we split into five groups of two to three people. Each group had their own pinhole camera to capture an image of spirals; each group took five pictures, one with each aperture size, using adjusted exposure times, and then developed the images in a darkroom. The apertures were taped onto the pinhole camera where the dime shaped hole was cut on the container.
After capturing all of the images, we surveyed 100 participants (20 per group) to determine which image they believed to be the sharpest and clearest. Each group directed the survey participants to look at the center of the images, and then asked them which they believed was the clearest and sharpest image.

Table 1- Exposure times for each aperture size.

<table>
<thead>
<tr>
<th>Aperture Size</th>
<th>Exposure time</th>
</tr>
</thead>
<tbody>
<tr>
<td>200μm</td>
<td>8 Minutes</td>
</tr>
<tr>
<td>250μm</td>
<td>6 Minutes 20 Seconds</td>
</tr>
<tr>
<td>300μm</td>
<td>3 Minutes 21 Seconds</td>
</tr>
<tr>
<td>350μm</td>
<td>2 Minutes 28 Seconds</td>
</tr>
<tr>
<td>400μm</td>
<td>1 Minute 46 Seconds</td>
</tr>
</tbody>
</table>

We analyzed our data using a two-tailed Z-test at 95% confidence. We made certain to meet the requirements of a Z-test: a large sample size taken randomly where it is assumed that the response of people surveyed is normally distributed within the population. We expected that a large majority (95%) of people would have a similar response, which would produce a curve similar to that of a normal population. To interpret our data, we expected that our values from the Z-test would fall between -1.96 and 1.96. This would indicate that we should accept our hypothesis, and any value outside of those values would indicate that we should reject our hypothesis.

RESULTS

Our results as shown in the pie chart (Fig. 10.) indicated only 15% of survey participants chose the picture from the 300 micron aperture as the picture with the best clarity and sharpness. Additionally, 59% of the survey subjects chose the picture from the 250 micron aperture. The picture from the 400 micron aperture was not chosen by any of the survey participants. We used the 300 and 250 micron proportions to calculate our Z-statistic of -6.71 which was outside of the -1.96 to 1.96 range of values for the Z-test. We then calculated the confidence interval between the expected proportion of people that selected the 300 micron picture compared to the people that chose the 250 micron picture. The confidence interval values range between .245 and .585. Since these values were both positive, there is a significant difference between these two percentages from the survey results.
DISCUSSIONS AND CONCLUSIONS

The results of the Z-test led us to conclude that the 300 micron aperture does not produce the clearest image for a pinhole camera with focal length of 67.5mm. We therefore rejected our research hypothesis. Since the 250 micron aperture proportion had the highest percentage (59%), we conducted Z-tests to see if there was a statistical difference between the 250 compared to the 350 micron (23%) aperture proportions and the 300 to 350 micron aperture proportions. For the 250 versus the 350 micron aperture proportion, we found a Z-statistic of -7.32 and the confidence interval fell between .152 and .197 (refer to Z-test calculations). Since -7.32 is less than -1.96 and the confidence interval is positive, we conclude that the 250 micron aperture proportion and the 350 micron aperture proportion are statistically different. For the results for the 300 micron (15%) aperture proportion compared to the 350 micron aperture proportion, we found a Z-statistic of 2.24 and the confidence interval fell between .26 and .50 (refer to Z-test calculations). Since 2.24 is greater than 1.96 and the confidence interval is positive, we found that the 300 micron aperture proportion and the 350 micron aperture proportion are statistically different. Based on these results, we determined that there is a difference between the 250 micron aperture proportion compared to the 300 and 350 micron aperture proportions. Therefore, the 250 micron aperture may be the optimal pinhole size for a pinhole camera with focal length of 67.5mm.

If the 250μm aperture size really was the clearest then maybe our constant was wrong. We used the constant, 2.44, in the formula \( d = \sqrt{C \lambda f} \) based on the Airy disc for sharpest image; this constant gave us a size of ~300μm, and we found that it was not the optimal size. Lord Rayleigh suggested a correction factor that proposes using a constant of 3.66 for images that are at least 1 meter away from the aperture. Our image was less than a meter away and that may have influenced our results. Using the most chosen aperture size, 250μm = \( \sqrt{C \lambda f} \), we
found the constant of 1.73 would better predict our results. Future studies could determine if the constant used in the formula is influenced by the distance the image is from the aperture. The constant could be influenced by the wave length, of light, and the focal length, making these important factors to study.

If the 300µm aperture should have been the best size then these factors may have contributed to our results. One factor is the difference in contrast of the images, which is the difference between the dark and light areas (Fig. 11). As seen in Figure 11, the left image has high contrast and at a quick glance may appear clearer than the right image, but this is the same picture just adjusted for exposure. It was hard to control exposure with homemade shutters, which may have influenced contrast. One group’s surveys contained an outlier. Four of the five groups had 2 or fewer people choose the 300µm image as the clearest, while one group had eleven participants choose this image as the clearest (Table 2). This particular image had higher contrast than the other images the group used. If participants only looked quickly at the image, they may have selected one with more contrast without looking at detail.

![Fig. 11.- Difference in contrast between pictures of the same image.](image)

Table 2- Raw data for each group and the totals for each aperture size.

<table>
<thead>
<tr>
<th></th>
<th>200µm</th>
<th>250µm</th>
<th>300µm</th>
<th>350µm</th>
<th>400µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
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<td>Group 2</td>
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<td>Group 3</td>
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<td>Group 4</td>
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<tr>
<td>Group 5</td>
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<td></td>
</tr>
<tr>
<td>Total</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Percentage</td>
<td>3%</td>
<td>59%</td>
<td>15%</td>
<td>23%</td>
<td>0%</td>
</tr>
</tbody>
</table>

= 100%
Another factor was that the surveys were not conducted in a controlled environment with consistent lighting. Some groups conducted their surveys outside, others inside, and some at a pool, where some participants wore sunglasses. To improve the results, it would help to conduct the surveys under the same conditions.

Our study was limited by available apertures. A wider interval of aperture sizes could have been used to better show the difference in clarity for the larger or smaller apertures. A range of apertures between 350μm and 250μm would determine a specific aperture size where an image appears the clearest.
REFERENCES CITED


