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Investigating Laser Speckle

Liam Becker[1]

[1] *University of Washington - PHYS 331*

ABSTRACT

Laser speckle is an optical phenomenon in which highly-coherent (usually laser) light is scattered off of a rough surface, creating an interference pattern an observer sees as a disk of light and dark dots, or "speckles" on the scattering surface. The pattern appears to behave very unnaturally when compared to the light we observe in everyday life—the pattern is always "in-focus" to the observer, regardless of where their eye may be focused, the pattern "zooms" in or our as an observer moves radially with respect to the scattering surface, and the pattern appears to "move" along the disk of light in varying ways with different colors and for different observers.

In this work we attempt to combine our knowledge of optics theory with observations of laser speckle to describe the mechanisms behind the various sub-phenomena and derive a model to describe the way an observer may experience laser speckle. We go through our basic observations and explain how aspects like wavelength and visual acuity will change the observed behavior of the pattern.

1. INTRODUCTION

Laser speckle is a pattern of light and dark points, or speckles, that appear when laser light is scattered off of an optically rough surface. I initially noticed the existence of this phenomenon when touring a quantum computing lab in the basement of the University of Washington's Physics and Astronomy Buildings for my Astronomy 192 (Pre-Major in Astronomy Program) course in Autumn of 2022. The lab had a green laser going through many mirrors, beam-splitters, and other optical devices I was unfamiliar with, but I was intrigued by the strangely-moving array of green dots littering the lab table. When I brought the pattern up to the graduate student running the tour I was met with the deeply unsatisfying answer of "I don't actually know."

Clearly, this event has stuck in my mind for almost 2 years, such that when I saw it again during our Physics 331 (Optics Lab) lectures during this quarter, I knew exactly what my GREEN TIME project would be. During both of the GREEN TIME sessions, my collaborators (Claire Atkinson and Jasper Gray) and I investigated how laser speckle arises and how it is perceived by the human eye. Combining our observations with our knowledge of optical phenomena and the literature we could find, we worked to craft a theory describing the laser speckle phenomenon, as detailed in the rest of this report.

2. EXPERIMENTAL SETUP

Our experiment comprised of a red He-Ne laser ($\lambda = 632.8\,\mathrm{nm}$) and a green He-Ne laser

Corresponding author: Liam Becker
liamb27@uw.edu

($\lambda = 543.5\,\text{nm}$), put through a microscope objective and pinhole to simulate a point source, and cast onto the target screen, as shown in Figure 1. We also attempted to use a lower-quality blue laser ($\lambda = 405/406\,\text{nm}$), but ultimately chose to stick to the red and green ones, due to concerns about the reliability of observations from a laser of such disparate quality.

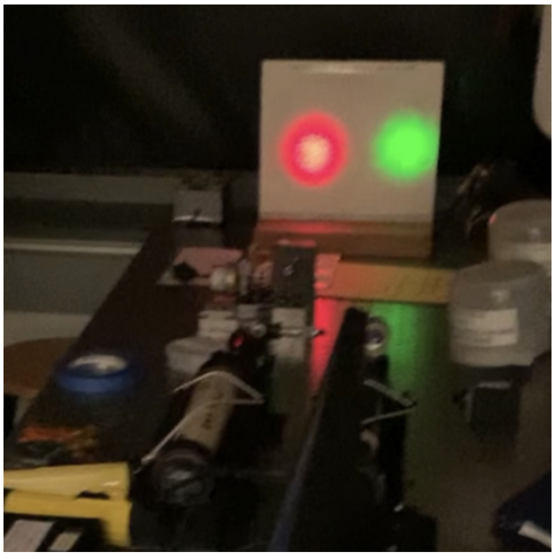

Figure 1. This is a bad angle, but the red laser (left) and green laser (right) can be seen passing through microscope objectives and pinholes, illuminating the target screen at the end of the bench.

Our group effectively consisted of 4 observers: one slightly hyperopic observer (Claire), one almost perfectly emmetropic observer (Liam w/ glasses), one slightly myopic observer (Jasper), and one very myopic observer (Liam w/out glasses), hereby referred to as HO, EO, MO, and VMO, respectively.

3. OBSERVATIONS

We noticed 2 main aspects of the speckle pattern: the appearance of the stationary pattern and the movement of the speckles. These will be discussed separately in the following sections.

3.1. *Stationary Speckles*

When observing the light cast onto the viewing screen, an observer sees a disk of color seemingly overlaid with a pattern of bright and dark spots that fade away at the edges of the disk. In our exploration of the phenomenon, we saw the size of the speckles vary due to a few factors. As one approached the screen onto which the light was incident, the speckles appeared to become smaller and more numerous, while observing the screen from farther caused them to decrease in number and increase in size (Hecht 2017). The effect could be compared to "zooming out and in" (respectively) with constant aperture on an array of fixed points.

A puzzling characteristic of the speckle pattern is the fact it always appears in focus. Usually, when an observer focuses their eyes on a target, the world appears blurry aside from a narrow depth of field in which the environment appears clear. Laser speckle, however, does not follow this pattern; no matter what distance an observer focuses on, a pattern always appears to be in perfect focus.

3.2. *Speckle Movement*

We also observed the unnatural movement of the speckle pattern with respect to other objects in the environment. When an observer moves their head in any direction (in this study we focused on lateral movements), the speckles appear to move at a rate different to that of the scattering surface. Using the analogy from Section 3.1, it is as if, when the observer moves their head, the aperture moves and seems to "scan" along the fixed points in a way that doesn't line up with the movement of the observer.

If an observer moves their head to the left and observes the speckles also moving to the left with respect to the screen, we have chosen to call this "coupled" movement. The inverse, where a leftward movement of the observer's head causes a rightward movement of the speckles, we have chosen to call "anti-coupled" move-

Table 1. The perceived movement of the speckle pattern for each laser, by each observer.

Observer	Red (632.8 nm)	Green (543.5 nm)
Claire (HO)	coupled	coupled
Liam with glasses (EO)	coupled	anti-coupled
Jasper (MO)	anti-coupled	anti-coupled
Liam w/out glasses (VMO)	anti-coupled	anti-coupled

ment. In Table 1, we list the speckle movement perceived by each of the four observers for each of the lasers we used.

Comparing the speed of speckle movement is difficult between observers due to the individual nature of perception, so it is fortunate that EO and VMO are the same person (me!) and can thus be directly compared. VMO observed significantly higher speckle velocities when compared to EO for both lasers, suggesting that visual acuity is a factor in the speed of speckle movement (a.k.a. speckle velocity). When observing the speckles, it was noted that

$$G_{VMO} < R_{VMO} < G_{EO} < 0 < R_{EO}, \tag{1}$$

where G and R represent the speckle velocities for the green and red lasers, respectively, coupled velocity is positive, and

$$|G_{VMO}| > |R_{VMO}| > |G_{EO}| > |R_{EO}|. \tag{2}$$

We see that VMO observed faster motion for both lasers, and that both observed the red speckles moving slower than the green speckles.

4. OPTICAL THEORY

Before analyzing our observations, we will briefly review the relevant optical theory required to understand the mechanisms behind laser speckle.

4.1. *Interference and Fringes*

When multiple waves pass through the same point in space, the values from each wave are superposed and added together to get the resulting amplitude at that point. “In-phase” waves interfere *con*structively and add their amplitudes to get a larger value, while “out-of-phase” waves interfere *de*structively and subtract their amplitudes to get a smaller value. Extrapolating this process across regions of space creates interference patterns, like those seen in Figure 2, where one can observe light and dark hyperbolic fringes of constructive and destructive interference. For sources with the same wavelength, a difference in the distance from some position to each of the sources (so-called “path-length difference”) determines the interaction between the waves at that source—if the path-length difference between the two waves is half of the wavelength, they interfere completely destructively (Hecht 2017).

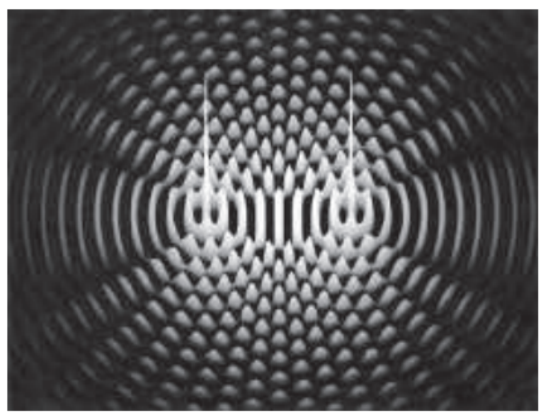

Figure 2. The interference in the electric field along a plane containing 2 in-phase point sources of light (Hecht 2017).

Fringes can be either “real” or “virtual” and “localized” or “non-localized” in space. Real fringes occur where light rays of the requisite path-length difference converge to a point in space, while virtual fringes appear when the rays must focused with additional optics to converge.

The eye of an observer viewing a real fringe would focus the diverging light from where the rays converged and the fringe would appear to the observer as existing at that point of convergence. For a virtual fringe, the eye focuses incident rays and the observer perceives them to have diverged from a point in space. These cases are illustrated in Figure 3.

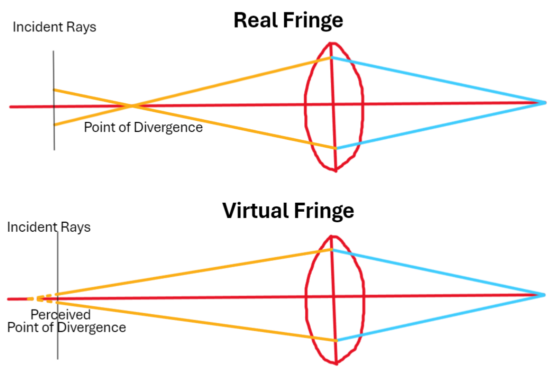

Figure 3. Ray diagram showing how real and virtual fringes can be observed. The lens shown is meant to be the lens of the eye with the light blue rays converging on the retina to the right.

Localized fringes can only be observed in a specific location, while non-localized fringes are observable continuously in space. An observer can see the same non-localized fringes at different points in space but cannot do the same for localized fringes (Hecht 2017).

4.2. *Coherence*

In a few words, coherence is the ability for a wave to interfere. In significantly more words, coherence describes the predictability of a wave source; if a source is highly spatially coherent, one can take a snapshot of a wave in time and reliably trace it in space; if a source is highly temporally coherent, one can predict the behavior of the field at a point in space over time. The light from a laser arises due to the stimulated emission of radiation—a process wherein photons of a certain energy stimulate the emission photons of the same energy from atoms inside a laser, as shown in Figure 4 (Hecht 2017). This radiation is in-phase and exhibits high spatial and temporal coherence, making laser-light very susceptible to interference with itself.

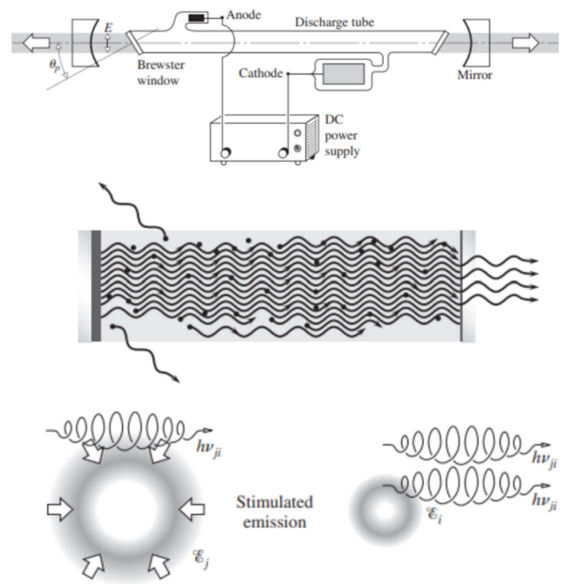

Figure 4. (Top) A simple He-Ne laser. (Middle) Diagram showing the coherence of laser light. (Bottom) Schematic showing stimulated emission of light (Hecht 2017).

4.3. *The Human Eye*

In very basic terms, the human eye consists of a variable-focal length lens which focuses light onto the light-detecting cells of the retina. The eyes and brain work in tandem to bring the world into focus by pointing each eye and adjusting their focal lengths in order to maximize the contrast of the desired object (Doherty 2006).

The eye can only focus on a narrow band of distance at a time, so it must change its focal length to change what an observer can see clearly. Via a process called "accommodation," ciliary muscles in the eye contract, moving forward and allowing the anterior zonular fibers (which hold the lens under tension, flattening its shape) to relax (Goldberg 2011). This reduction in radial tension lets the internal elastic forces of the lens change its shape, becoming rounder and thicker, decreasing the focal length of the lens such that a nearby object comes to focus on the retina of the eye (Hecht 2017). The effect of accommodation can be seen in Figure 5.

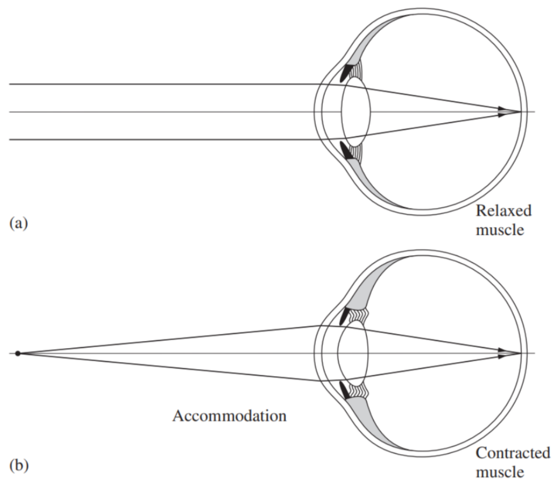

Figure 5. Schematic of a relaxed (a) and accommodated (b) eye. Adapted from Hecht (2017).

A "normal" or *emmetropic* eye is one that focuses parallel rays on the retina when unaccommodated, meaning its relaxed focal point lies on the retina. In contrast, a "nearsighted" or *myopic* eye is one whose relaxed focal point lies *in front of* the retina, while that of a "farsighted" or *hyperopic* eye lies *beyond* the retina (Hecht 2017). Figure 6 compares these three types of eyes.

An object in focus to a fully unaccommodated myopic eye is said to lie at the eye's "far point," beyond which any object will come to a focus in front of the eye, appearing blurry on the retina (Hecht 2017). Aptly, the far point is the farthest an unaided (i.e. without glasses) myopic eye can see clearly, and is the distance the eye will focus at when attempting to view objects beyond the far point.

These eye defects occur due to errors in the shapes of the lens and cornea, a non-spherical retina, or some combination of the two. An eye with non-symmetric defects (e.g. myopic along one axis and hyperopic along another) is said to have *astigmatism*.

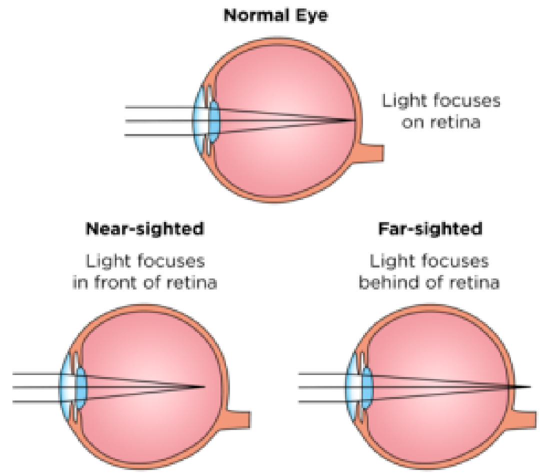

Figure 6. Diagram comparing the focal points of myopic and hyperopic eyes to that of a emmetropic eye (Eyes For Life 2018).

4.4. *Chromatic Aberration*

Dispersion is the reason lenses refract wavelengths of light differently, like how sunlight through a prism is dispersed into a rainbow. In lens-based optical systems, dispersion will cause different colors to come to a focus in different locations, known as longitudinal chromatic aberration, shown in Figure 7.

The wavelength-dependence of dispersion in the eye focuses red light behind the retina and blue light in front of the retina, while green wavelengths will focus approximately on the retina (Hecht 2017). The effect is rarely noticeable, but is significant in some cases.

4.5. *Parallax*

Humans employ parallax to judge the distances of objects every day, to the point that most people aren't even aware that they are using it. Depth perception is a complex combination of monocular and binocular cues, but this work will only reference motion parallax.

When an observer moves, nearby objects appear to move faster than those farther away;

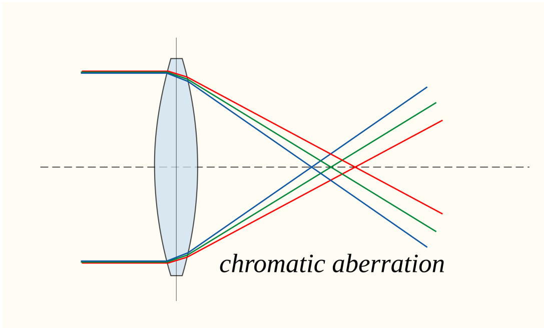

Figure 7. Diagram showing how different colors of light are refracted; shorter bluer wavelengths are refracted more, while longer redder wavelengths are refracted less (Mellish 2006).

for example, smudges on a window move faster than a nearby building which itself moves faster than a far-away mountain (Wikipedia contributors 2024). Additionally, the direction of this motion can change depending on where the observer is setting their focus; the reader may hold a finger on each hand at different distances from their eye and notice how the other finger moves. When focusing on the nearer finger, the farther one exhibits coupled motion (as defined in Section 3.2), while focusing on the farther finger causes the nearer one to exhibit anti-coupled motion (Pengra 2024).

These two examples of motion parallax—hereby referred to as *speed* and *direction* parallax—allow us to determine the distances of objects relative to one another.

5. ANALYSIS

This analysis is split into sections describing the formation of the speckle interference pattern, the perception and location of laser speckle for myopic and non-myopic observers, and finally the perception of speckle size as it relates to distance from the scattering surface.

When comparing observers, I will only use my own observations (EO and VMO) to reduce the affect of other variables in perception of the phenomenon.

5.1. *Speckle as Non-Localized Interference*

As mentioned in Section 2, the setup approximates a point source of coherent light casting a disk onto the optically rough scattering surface. "Optically rough" refers to the fact that the wavelength of the light is smaller than the height of surface features, which itself is smaller than the coherence length of the light (Hecht 2017).

After striking the scattering surface, the incident light is reflected in many directions and at many different distances from the source—the surface features may seem small, but on the scale of highly coherent laser light, these variations are significant enough to cause interference effects. This is illustrated in Figure 8, where scattering causes meaningful path-length differences without any clear pattern, leading to the random appearance of the speckles.

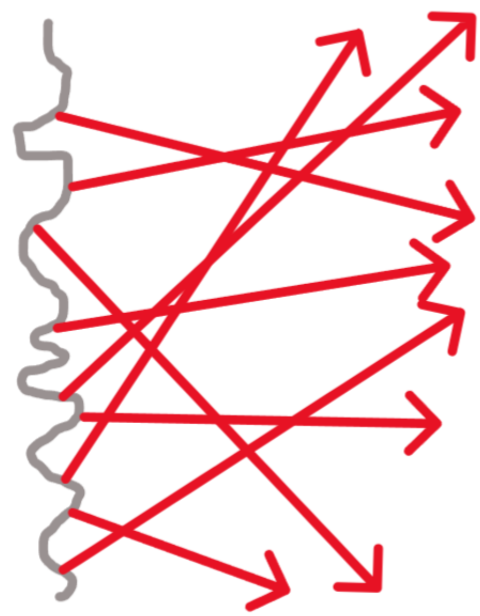

Figure 8. Illustration shows some of the many reflected rays off of an optically rough scattering surface. The irregular surface causes the resulting interference pattern to lack structure (e.g. lines or concentric rings).

Due to the many scattering angles, some rays will converge in front of the observer and be visible as real fringes, while others will be parallel or diverge and thus be virtual fringes, just like in Figure 3. In fact, we can take these fringes to be so numerous that an eye focused anywhere in front of or behind the screen should be able to focus on a set of fringes, meaning laser speckle is a non-localized interference pattern.

5.2. *Locating the Speckle*

While the entire collection of fringes exists in space, an observer can only view a single set in focus—that which is located (or appears to be located, in the case of virtual fringes) precisely where their eye is focused. If the eye is focused in front of the screen, the observer will see real fringes, while focusing behind the screen will be virtual fringes. In either case, the eye will always observe in-focus sets of fringes, as was observed in Section 3.1.

An observer may only see light which reflects off of the scattering surface and enters their eye. This effectively creates a "cone" of visible speckles whose base is the disk of light cast onto the scattering surface and vertex lies approximately on the observer's retina.

The intersection between the observer's plane of focus and this cone of visible speckles forms a "visible disk" in space and is the only portion of the interference pattern visible to an observer. The visible disk appears to lie on the screen, as is illustrated in Figure 10.

5.2.1. *Myopic Speckle*

As stated in Section 4.3, a myopic eye looking at an object beyond its far point will be fully unaccommodated and thus focused at the far point. In the case of VMO, this point is significantly closer than the screen and therefore, VMO observes fringes much nearer than the screen. VMO sees anti-coupled movement for both lasers, confirming with direction parallax that both sets of fringes are in front of the scattering surface.

Since red speckles move slower than green speckles in all cases, they *must* be farther away due to speed parallax. This statement seems to be at odds with the previous assertion that the eye of VMO is focused at the far point for both lasers—in fact, the eye is equally unaccommodated in both cases, however, as a result of chromatic aberration, red light is refracted less in the eye than green light. If the red fringes originated from the same distance as green, the green ones would focus on the retina, yet the red ones would focus behind the retina and be blurry. In reality, VMO sees both colors clearly, meaning the red fringes focused on the retina must be coming from farther away from the eye than the green ones.

5.2.2. *Non-Myopic Speckle*

A non-myopic observer, such as EO can place their focus approximately in the plane of the scattering surface, observing the screen clearly. Assuming the white screen is focused on the retina, chromatic aberration causes green fringes at the same location to be focused in front of the retina and red ones focused behind.

Again, a set of fringes must always be focused on the retina, and for this to be true, the in-focus red speckles must come from *behind the screen*, while the in-focus green speckles must originate *in front of the screen*. This is illustrated in Figure 9.

Direction parallax says that objects farther than the screen (red speckles) exhibit coupled motion, while objects nearer than the screen (green speckles) exhibit anti-coupled motion—exactly as observed by EO in Table 1.

5.3. *Speckle Size*

This discussion of speckle size follows from the theory outlined above and lacks sufficient data and observations to prove its accuracy.

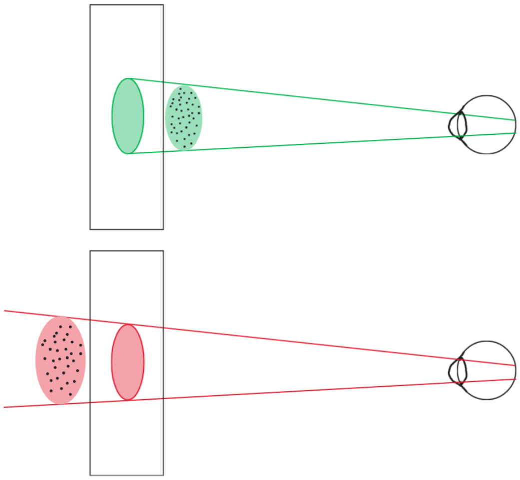

Figure 9. **(Top)** EO focuses on green fringes *in front* of the screen. Moving the eye up in the plane of the page will shift the visible disk *up*, allowing new speckles to be visible. Compared to the screen, the speckles would appear to be moving *down*. **(Bottom)** EO focuses on red fringes *behind* the screen. Moving the eye up in the plane of the page will shift the visible disk *down*. Compared to the screen, the speckles would appear to be moving *up*.

Consider two observers of green speckle, EO and VMO, located such that they are focused at precisely the same distance from the scattering surface (and that the screen is still beyond VMO's far point). If both observers were to back away from the screen by the same amount, they would no longer observe the same pattern, shown in Figure 10.

As EO moves away from the scattering surface, their focus remains at the same location, yet their cone changes shape. The vertex moves farther from the base, causing the angle between the base and the wall to approach perpendicular. The radius of the cone decreases less rapidly with distance from the screen, meaning the visible disk grows and holds more speckles than before.

From the perspective of EO, the disk stays exactly the same size on the screen, just with more speckles, meaning the size of each speckle must decrease. The reduction in size and increase in number makes it look like the speckles are "zooming out."

Since the plane of focus is always at VMO's far point, it moves away from the screen as they walk backwards. As VMO's cone stretches, the radius of their visible disk shrinks as it gets proportionally closer to the vertex.

Assuming the interference pattern doesn't significantly change in size with distance, the individual speckles maintain a relatively consistent angular size as VMO backs away, while the angular size of the disk significantly shrinks. From VMO's point of view, the speckles grew in size and decreased in number, appearing as if the pattern "zoomed in."

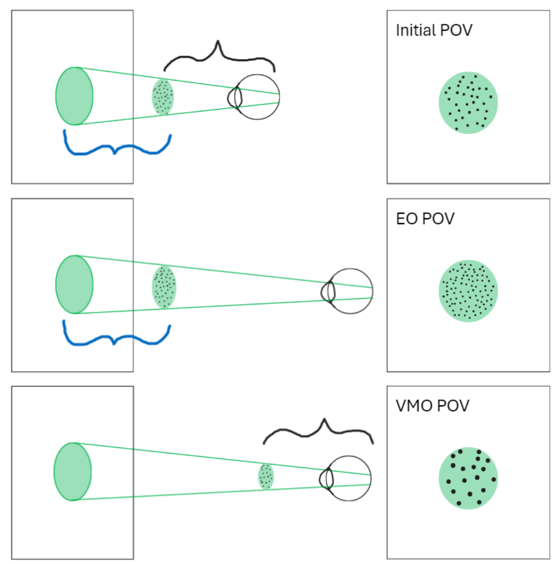

Figure 10. **(Top)** The initial positions of EO and VMO, such that they both observe the same pattern. **(Middle)** EO walks away while maintaining the same plane of focus (blue brackets, below cones). The cone changes shape and the visible disk grows, making the speckles appear to "zoom out."**(Bottom)** VMO walks away while focused at their far point (black brackets, above cones). The plane of focus moves closer to the vertex, shrinking the visible disk; speckles appear to "zoom in."

When observing speckle behind the scattering surface (EO observing red), moving farther from the screen causes the visible disk to *shrink* as the wall becomes more perpendicular. The pattern would appear to zoom *in*, opposite to what is observed with speckle in front of the screen.

6. CONCLUSIONS

The various phenomena described in Section 3 can be explained as follows: a point source casting highly coherent laser light incident on an optically rough surface is scattered, forming a non-localized collection of real and virtual interference fringes on either side of the scattering surface due to path-length differences caused by the scattering.

The collection of fringes all simultaneously exist in space, however, an observer may only see light which reflects off of the scattering surface and enters their eye, forming a cone whose base is the disk of light cast onto the scattering surface and vertex lies approximately on the observer's retina. Intersecting an observer's plane of focus with this cone forms the visible disk—the portion of the interference pattern that the observer can see.

When an observer moves, their cone and visible disk move through the interference pattern, appearing as if the speckles are moving on the screen. The motion of the disk and the speckles are opposite, such that a disk movement to the right causes the speckles to move left.

As a non-myopic observer attempts to focus on the screen, longitudinal chromatic aberration causes their focal point (and therefore visible disk) to vary with color—red focuses beyond the screen, green focuses in front of the screen. Observing the speckles from opposite sides of the screen causes the dichotomy of coupled and anti-coupled motion for red and green, respectively.

For speckles in front of the screen, this observer's visible disk will stay in place and increase in radius as they move away from the scattering surface, causing the pattern to appear to zoom out. In the same scenario for speckles behind the screen, their visible disk will instead shrink and the pattern will zoom in.

A myopic observer sufficiently far away from the screen will only have a focal plane lying at their far point. Therefore, their visible disk lies in front of the scattering surface for all colors and they will observe exclusively anti-coupled motion. As this observer backs away from the screen, their visible disk will shrink in size and the pattern will appear to zoom in.

7. FURTHER WORK

Unfortunately, human sight is a complex process with many variables that we were unable to control for in our experiment. Things like the shape of each person's retina, the differences in chromatic aberration for each individual's eyes, and even differences in the ways each of our brains process sensory information could make comparison difficult between observers.

Seeing as I have the same eyes with or without my glasses, I was able to directly compare the perception of EO and VMO while ignoring most of these variables—aside from one. Introducing an additional lens into my optical system could affect the chromatic aberration I experience. If dispersion is higher due to my glasses when compared to someone like Claire (HO), who should also be able to focus on the scattering surface, it might explain why she exclusively saw coupled motion. If her eyes disperse green light behind the screen when mine disperse it in front, that would produce such a discrepancy in the direction of motion.

In the process of writing this paper, additional avenues of inquiry have occurred to me, the first of which being the effect of astigmatism on speckle perception. I noticed that the motion I see when moving my head vertically would sometimes differ from that of lateral movement and I believe this to be a result of my astigmatism—if my eyes are differently defective on the vertical and lateral axes, it would be interesting to look into how that manifests in my perception of laser speckle. Perhaps I will be able to use this vertical motion as additional proof of the theory described in this work.

We observed that moving the scattering surface caused the speckles to move so quickly that their motion became blurred; I would be interested in observing how movement of the screen would affect the pattern if it were moved slow enough for the motion to be perceived. This could potentially be achieved with the use of electronic motors.

Finally, I assumed in Section 5.3 that the interference pattern doesn't significantly change with distance, and didn't explicitly prove that it is so. When observing the speckles, changing one's distance from the screen truly does look like the speckles are just zooming in and out—the actual pattern doesn't appear to change. From my knowledge of other non-localized interference patterns, I assume the fringes spread out from each other as they get farther from the screen, but my memory isn't good enough to prove one way or another.

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