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Perceptual Distortions

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Perceptual Distortions

Abstract
This research project attempts to quantify the subjective quality of color vision that artists like Josef Albers have explored through their art. It is widely understood by artists and scientists that the appearance of a surface color is affected by its context. However, there are many questions yet to be answered about the specific spatial relationships between colors. This experiment uses an achromatic adjustment task to compare the context effect of colors inside and outside of a grid containing a test square. The results show that the color inside the grid has a greater affect on the appearance of the test square than the color outside the grid. This result was found across observers without exception. The idea that colors affect each other more when placed closer together may seem intuitive, but our results serve to confirm this assumption and to set the groundwork for further studies to develop a general theory of color interaction.

Keywords
perception, Joseph Albers, color constancy, visual studies, David, Brainard, David Brainard

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Perceptual Distortions

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Introduction

We, as viewers, are constantly bombarded with visual information. Light of seemingly infinite patterns of intensities, wavelengths, and spatial arrangements enters our eye, impinges on the surface of our retina, and through a complicated and fascinating process, it results in conscious awareness of a visual world. Vision is arguably our most valuable sense; we gain access to an immense amount of information through this modality, and, unlike the processes of taste, smell, and touch, we obtain this information quickly and without the necessity of physical contact with the observed objects. But because most of us rely so heavily on vision, we are particularly susceptible to its deceptions. This deception originates from an inherent characteristic of vision: we do not directly perceive the physical features of light. Rather, we experience "the interpretative mental symbol of the object."[1]

Formulating a theory about what happens between light and perception has challenged scientists for hundreds of years. The earliest conundrum involved Kepler's theory of the retinal image as an inverted picture. Kepler was convinced of this aspect of optics, but he could not explain how the retinal image is "flipped" so that we do not perceive an upside down world. He speculated that a spirit inside the brain allowed the image to be perceived by the soul.[2] Some early theorists made a similar assumption that involved a "homunculus" who would look at the image on the retina and then somehow transmit information about what he saw to the soul, resulting in visual awareness. Today there is general

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[1] Kemp, *The Science of Art*, 241.
[2] Lindberg, *Theories of Vision: From Al-Kindi to Kepler*, 203

agreement that this is not the way perception works, but the details of the process are still largely mysterious.

The optical and perceptual aspects of visual perception are of particular interest to visual artists who try to convey both the subjective and objective aspects of vision to the viewer. It is especially relevant for artists who aim to achieve a high level of verisimilitude in their portrayals of natural scenes. Theoretically, an artist could produce a surface characterized by a pattern of light reflection that would yield a similar percept to the pattern of light emanating from a natural scene. The two distal stimuli[3] could produce the same proximal stimulus[4] under the correct viewing conditions. Metameric stimuli exist because the visual system cannot discriminate all wavelength patterns[5]. Additionally, a similar proximal stimulus may occur because the image is "flattened" at the retinal stage of vision whether we are viewing a three-dimensional scene or not; the light reflecting off of a flat surface can potentially lead to a similar pattern of retinal stimulation as a three-dimensional scene. The perceptual system may extrapolate depth from monocular and binocular cues, but we do not directly perceive depth. In fact, illusions of depth abound – autostereograms, also known as Magic Eye patterns, are an example of two-dimensional surfaces that can result in depth perception by manipulating binocular cues.

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[3] Objects in the world; in this case the distal stimuli are the painting and the scene.
[4] The pattern of stimulation of the cells of the retina.
[5] Metamers are different wavelength patterns that produce the same photoreceptor responses and thus appear identical. Most people possess three types of color-processing photoreceptors that each respond to a broad range of wavelengths. As a result, light with different wavelength distributions could invoke the same magnitude of response in each type of photoreceptor. It is from the comparison of responses of all three types of receptors that the brain gains color information, so light that invokes the same cone responses will be indistinguishable at all levels of processing.

But translating the three-dimensional scene onto a two-dimensional surface accurately and convincingly has proved to be a complex and formidable challenge for artists and scientists. A major issue needs to be resolved: before the artist can translate the physical aspects of the scene into marks and paint, his visual system has already translated the scene into perceptual correlates. As a result, he cannot form a strategy for drawing or painting based on what is actually there in front of him, but only on his mental representation of what is there. The physical reality of the light and the perception of that light are correlated but invariably distinct. When a second party finally observes the painting, already twice distorted by the artist's perception and the process of painting, his perceptual processes must reinterpret the scene. At this point, the spectator's perceptual representation of the painting has possibly diverged greatly from his potential representation of the original scene.

Some proposed solutions are simply infeasible. Pieter Camper, an anatomist and painter, recognized that the eye has greater focusing power near the center of the visual field. He believed that painting peripheral areas of a scene out of focus would compensate for this issue of acuity.[6] However, in practice this strategy would only serve to exacerbate the problem. The blurred area of the painting would become more blurred when the viewer looked at the center, and the entire painting would appear blurred if the viewer looked at a peripheral section. Camper's solution indicates that he attempted to take vision into account while painting but not to *compensate* for the heterogeneity of the visual field.

It may not be possible to avoid some level of distortion. The actual process of painting will never be perfected, as the medium and the motor skills of the painter are limiting factors. Additionally, a percept is an individual and unique phenomenon. No two people will experience the exact same percept, even if they

[6] Kemp, *Science*, 236

were to experience the same object from the same point of view. This is because their awareness of the object is mediated by past experience in the form of associations and biases. As a result, an artist should never expect his painting to induce the same percept that he originally experienced or for two people to perceive the painting the same way. To attempt this, I believe, would be futile.

An artist can try to paint in such a way that, under the correct viewing conditions, the visual symbols of the painting will lead to a similar percept than if the viewer had witnessed the actual scene. As Helmoltz noted,

> The artist cannot transcribe Nature; he must translate her; yet this translation may give us an impression in the highest degree distinct and forcible, not merely of the objects themselves, but even of the greatly varied intensities of lights under which we view them…Thus the imitation of Nature in the picture is at the same time an enobling of the impression on the senses.[7]

The painting and the scene will never be perceptually indistinguishable, – there will always be issues of acuity, motion parallax, and accommodation. However, the differences could be minimized such that an effective illusion could be conveyed. Indeed, all perception is essentially illusory, and realistic art necessitates that the artist is a great illusionist. The artist must utilize visual cues to encourage the incorporation of the image and the spectator's knowledge. Ultimately, the artist must be concerned with "the nature of our reactions to the physical world."[8]

This is not to say that extreme verisimilitude should be the goal of art in general. This is completely up to the individual artist, and I am not of the opinion that realistic art is necessarily superior to non-representational art. However, the fact remains that throughout history, especially before the advent of photography, many artists have tried to convey natural scenes as realistically as possible. Even

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[7] Helmoltz, *Popular Lectures on Scientific Subjects*, 135-6
[8] Gombrich, 44

more have attempted to incorporate some aspect of nature (e.g. the color or texture of the clouds) while compromising the accuracy of the overall representation in exchange for control of composition. The Scottish Philosopher Thomas Reid suggested, "the painter who strives to imitate nature may be regarded as attempting to capture the visual 'signs' of nature in a raw and directly available manner, before the intervention of interpretation."[9] To Reid, interpretation was the aspect of the perceptual process that utilizes tactile knowledge of the visual world based on past experience. This is just one of many ways that the perceptual process transforms the "'signs' of nature."

Perceptual Processes

The field of psychology is based on "the distinction between the objectively existing world and the perception of it."[10] Many, if not all, aspects of a percept do not exist without a perceptual system to create them. The main function of the brain's sensory processing system is to translate physical information, such as properties of light and pressure waves, into perceptual correlates. However, the brain does not necessarily translate these properties literally or in a one-to-one manner, nor is this an entirely passive activity. Perception is not simply awareness of sensory inputs. Rather, perception involves a complicated process of thought and problem solving in which the brain attempts to utilize physical information in an optimal manner. In all likelihood, a huge amount of information and number of processes, including "sense, knowledge, and inference,"[11] play a role in the creation of every percept. Individual physical

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[9] Kemp, *Science*, 238
[10] Arnheim, *Visual Thinking*, 5
[11] Gombrich, E.H., *Art and Illusion*, 13

differences in optics are accounted for in later stages of processing[12], and perceptual learning through sensory experience can recalibrate neuronal responses to reflect likely feature occurrences.

Because there are so many factors contributing to conscious awareness of sensory inputs other than the inputs themselves, "it is so hard for us all to disentangle what we really see from what we merely know and thus to recover the innocent eye."[13] Color constancy and shape constancy are processes that allow our perception of our surroundings to remain stable. They are ways that the brain tries to decide "whether the change is due to the object itself or to the context…otherwise he understands neither the object nor its surroundings."[14] Usually, this strategy is beneficial; it allows us to navigate the world effortlessly. Buildings do not seem to change shape as we walk around them, and surfaces do not seem to darken as a shadow passes. Gombrich observed the utility of this fact,

> Look around you in a lighted space and everything in it may look present and material and real; but even the most ordinary interior and the most familiar exterior enter your eyes through a complex of optical effects which you have learned to interpret…Noticing such tricks the eye performs on a daily basis would stall business; training the mind to see its own ceaseless activity of editing, erasure and comprehension in order to move about in the world of appearances would bring ordinary responses to a standstill.[15]

Without the ability to infer that shape and color changes are do to external factors and not caused by objects constantly morphing even the simplest task would be quite confusing. But as useful and necessary as these processes are, they can create a large division between the object in the world and the perceived object.

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[12] Artal, P., et al. (2004), Neural Compensation for the eye's optical aberrations, *Journal of Vision*, 4.4.4, 281-287.
[13] Gombrich, 12
[14] Arnheim, *Thinking*, 38
[15] Mannoni, *Eyes*, 17

Color Constancy

Color constancy allows us to see an object under different lighting conditions without it seeming as if the surface properties have changed. Take, for example, a piece of white paper with black text. In sunlight the black print might reflect more light than the white paper would under dim indoor lights. Yet, we tend to believe that we see a white rectangle with black symbols no matter the overall lighting. In other words, a black object in one context can actually reflect more light than a white object in another context without affecting perception.

Color constancy functions utilize relative intensities rather than absolute intensities. The white part of the paper is brighter than the text in any light, and so the overall contrast has not changed. The brain's color constancy mechanism can also cause "the same physical phenomenon [to] be seen and described differently by the same person in different optical contexts."[16] A gray patch seen in front of a white background will seem noticeably darker than if it is seen in front of a black background. If an artist were to trust his perception, he would paint this color incorrectly, and the observer of the painting would not experience the same color that the artist did while viewing the scene. Josef Albers explored this topic in depth, using his art to explore the effect of context on the appearance of colors.[17]

Shape Constancy

The retinal projection of an object depends on the viewer's spatial relationship with that object. This relationship is rarely stagnant; we move through the world, our eyes shift focus, and objects change position. As a result, we hardly ever see objects from an ideal viewpoint. Take, for example, a handful of coins. As a person counts his change, he perceives circles of different sizes, not

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[16] Kemp, *Science*, 261
[17] Albers, Josef, *Interaction of Color*

ovals with different degrees of ellipticality. But the projection of each of the coins on the retina is indeed an ellipse. Paying attention, one can see that a circle does take on an elliptical shape when turned, but knowledge of the "true" shape of the object still affects perception. "The perceiver does not only compare [the objects] with roundness but does indeed see roundness in them."[18]

Color and shape constancy are examples of perceptual processes that distort the world in a way that makes it easier to understand. They allow us to gain access not to raw, physical information about light, but rather to more indirect and meaningful representations. These representations are based on relationships rather than properties of isolated objects. For most people, this is the type of information that is useful and expected, and "without this faculty of man and beast alike to recognize identities across the variations of difference, to make allowance for changed conditions, and to preserve the framework of a stable world, art could not exist." However, as I have briefly discussed, it may be advantageous for artists to break down object representation into a more raw measurement of light in order to have control of the illusory affects of the painted scene. They may train their vision to "undo" perceptual processes like color and shape constancy and to become aware of a "lower" level of vision that exists before these processes occur.

Illusions

Illusions exploit the dichotomy between objective reality and subjective perception. Visual illusions, once viewed as "Devil's mischief," have been around for centuries. Seventeenth century intellectual interest in the acquisition of knowledge through the senses led to the use of illusions as fuel for the "intense

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[18] Arnheim, *Thinking*, 27

speculation about the interplay of perception and reality itself."[19] Illusions often illustrate the flaws of perception, but more often they rely on normal perceptual functions applied to unusual situations. A discussion of common illusions and their relevance to every day vision can help us to better understand the relationship of perception and the visual world, and it can further emphasize the nature of perception as an instrument of transmogrification rather than direct measurement.

One of the main jobs of perception is to disambiguate objects in the world. Any scene could be interpreted in an infinite number of ways, but we usually resolve the conflict and experience just one possible arrangement. An object will occlude another object placed behind it in space, so in this type of situation we normally perceive two complete objects offset in depth. However, it is possible that the objects lie in the same plane and that they simply fit together like puzzle pieces. Obviously, this is the less likely possibility, and the perceptual system is usually right to bypass this possibility in place of the other explanation.

However there are certain instances in which two or more interpretations of the scene are equally likely. In this case, the image has the potential to invoke multiple percepts. A classic example of this type of illusion is the Necker cube, which is perceived as switching between incompatible spatial arrangements. The ambiguous cube may have its front face to the right or the left of center (**fig. 1a**). We can see either arrangement, but we never perceive both at the same time. Another example is the duck-rabbit drawing (**fig. 1b**). Objectively, the image represents a duck *and* a rabbit. Subjectively, a subtle shift occurs between the two so perception of one occurs while perception of the other is suppressed. The image can only be seen as a duck *or* a rabbit.[20]

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[19] Mannoni, *Eyes*, 16
[20] Gombrich, 4-5

Perceptual processes also attempt to combine information about an object and its context in order to determine which aspects of its appearance are due to the object and which are due to its context. An object will appear to be painted in one uniform shade despite the shadows and highlights that characterize the light reflecting off of its surface. This is because the brain correctly infers that these effects are most likely a product of the interaction of the illuminant, the surrounding objects, and the object in question. This process helps us perceive the "reality" of the scene, which can also be described as the invariant properties of the objects. However, it can cause two instances of the same objective color to appear different, and it can cause different objective colors to appear indistinguishable. This may be because knowing about the light reflecting off of an object is usually not as important as knowing something about the invariant surface properties of the object.

The salience of this type of illusion can be seen in the famous Adelson checkerboard (**fig.2**). Square A and square B appear drastically different, but they are in fact the same shade of gray. The differing appearance can be explained by the fact that square B appears to be under shadow while square A appears to be fully illuminated. If two surface patches reflect the same amount of light, but they are exposed to different illuminants, then they would necessarily not reflect the same amount of light when exposed to the same illuminant. They have different surface properties. Our percept of the two patches reflects this inference of invariant features.

Artists' relationship with vision

Visual artists have often made the distinction between "seeing" and "knowing." There is the information that enters the eye, and then there is the transformation that it undergoes between the eye and conscious awareness. "What we get on the retina…is a welter of dancing light points stimulating the sensitive rods and cones that fire their messages into the brain. What we see is a stable world. It takes an effort of the imagination and a fairly complex apparatus to realize the tremendous gulf that exists between the two."[21] Processes such as color constancy and shape constancy make up part of the 'tremendous gulf' and involve abstraction "at the highest level of generality." However, an artist's task requires that he "leave the level of maximum generality and proceed to the necessary refinement of perception."[22]

But how can the artist 'leave' this level of perception? Many artists, whether consciously or not, are capable of practicing a way of seeing that is very different from the functional method of seeing that is utilized in every-day tasks. While most observers form percepts by taking context into account and then "subtracting" the effect of context on the viewed object,

> the training needed for realistic painting…requires that the student learn to practice 'reduction,' that is, to see a given color value as it would look through a narrow peephole, or the size and shape of an object as though it were flattened out on a two-dimensional plane. The difficulties met in such training show how unnatural it is to see out of context. However, if such a reductive attitude is attained, it shows a given object as changing its character when the context changes.[23]

This skill may not seem very practical outside of the realm of art, but it reflects a not uncommon goal of artists to paint "what is seen rather than what is known."[24] This 'reductive' ability may be what sets artists apart from non-artists as far as their method of seeing. In fact, much of art training is training to look. Art teachers recognize the importance of this skill, and they shape curricula around

[21] Gombrich, 46
[22] Arnheim, *Thinking*, 43
[23] ibid
[24] Kemp, *Science*, 243

the idea that the "pupils' difficulties [are] not due only to an inability to copy nature but also to an inability to see it."[25]

The inability to see nature forces amateur artists to substitute the symbolic for the visual. Children often draw the prototypical tree and beaming sun as they attempt to illustrate an outdoor scene. They place a strip of blue at the top of the paper to represent the sky - they know that sky is above rather than see that the blue field reaches all the way down to the horizon. Of course a child's tendency to be influenced by the symbolic nature of images does not end when adulthood begins. Our knowledge of objects often includes mental images. Most of us can conjure up a picture of a bird or a dog, and the immediate mental image is probably more likely to resemble a robin or a golden retriever than an ostrich or a chihuahua. The artist, therefore, faces a challenge when attempting to represent a less archetypical token of a category. The challenge is to avoid utilizing the more familiar token as the "starting point for the rendering of the unfamiliar; the existing representation will always exert its spell over the artist even while he strives to record the truth."[26]

In his classic volume, *Art and Illusion*, E. H. Gombrich discusses the shift from schema and formula to observation and imitation in the Western art tradition. The medieval distinction, he posits, was between the ideal and the particular. When an artist drew from life, he tended to force the objects in the scene to fit the ideal proportions (as determined by convention) and to attempt to "purify the world of matter, erase its flaws, and approximate it to the idea." Artistic "tricks," such as breaking objects down into a geometric skeleton, determined the appearance of painted objects to a greater extent than their objective appearances. However, schematic methods only work for the ideal

[25] Gombrich, 10
[26] Gombrich, 72

object, and representing the particular, unique manifestation of an object, remained a major artistic challenge.

The post-medieval artist, Gombrich argues, began to move away from the use of visual formulas and towards a desire to "wrestle with the unique visual experience which can never have been prefigured and can never recur." Schemata were still used, but as a starting point rather than as the image itself. Artists began to focus more on seeing instead of knowing. As an artist who possessed a deep understanding of this distinction, Constable reported that he often "tried to forget" his previous experience with images while sketching. His sentiment reflected a widespread attempt to "undo" – Constable used the word "forget" – visual processes while observing nature in order to "intensify the search for particular truths."[27]

Josef Albers displayed a particularly strong sense of the nature of perception through his paintings and writing. He stressed that an artist must develop a sensitive eye for color, and he believed that sensitivity could be obtained through experimentation. He was a proponent of practice before theory. He believed that experience through trial and error would help one gain an understanding of the consequences of the idea that "a color is almost never seen as it really is – as it physically is…In order to use color effectively it is necessary to recognize that color deceives continually."[28] Albers performed a series of studies of the interaction of colors. Although many artists recognized that colors affect each other, Albers performed formal "searches" to explore the way spatial relationships affect color interaction. He demonstrated a clear understanding of the distinction between subjective perception and objective reality by defining the

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[27] Gombrich, 133-152
[28] Albers, 1

physical properties of a color as "factual" and the perceptual correlates as "actual."[29]

Albers repeatedly illustrated that the same color can be made to appear different depending on its context. He also showed that different colors could be made to look the same. Based on his interest in this particular effect, it seems obvious that Albers recognized the need to distort colors during the art making process in order for them to look how the artist intended them to look when the artwork is finished. The same object placed in different contexts must be painted in different colors. These different colors will come to appear the same, and the objects will be recognized as similar.

Another example of Josef Albers understanding of the necessity of distortion is his discussion of the Weber-Fechner Law. He once again discriminates between the "physical fact" and the "psychological effect." If the physical fact is a linear progression of intensities, in other words a linear gradient, the psychological effect will be more like a log function. Each linear increase in intensity will correlate with less of an increase in perceptual intensity than the last. Therefore, Albers states, in order for the psychological effect to resemble a linear gradient, the physical fact must actually be a multiplicatively increasing gradient. Albers solution for dealing with the Weber-Fechner law requires that the artist manipulate the image, and it bases the manipulations on an understanding of perception.[30]

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[29] Albers, 9
[30] Albers, 54-58

Tools

Introduction

Our perceptual system works as a filter, "purposive and selective."[31] We perceive a specific range of wavelengths, light levels, and spatial resolutions. The system transforms the physical properties of light within these ranges into perceptual correlates so we can indirectly access information that is useful for survival and day-to-day interactions. Yet an artist may need to gain access to information outside the scope of human perception or at least to develop away to visually convey this information. Historically, artists have turned to optical devices, tools, and geometric systems in order to translate physical properties of the world into perceptual properties comprehensible to the human observer.

For hundreds of years, many prominent artists have displayed, through writing, theories, inventions, and practice, an interest in "visual science and its instrumental corollaries."[32] Their interest has yielded interesting mechanisms that imitate nature and often produce strikingly salient illusions of a real visual space. These mechanisms reflect a desire on the part of their inventors and users to understand the relationship between objectivity and subjectivity in vision. Scientific and artistic exploration fueled this desire, as did a "crisis of doubt in the reliability of perception."[33]

Nonetheless, some artists and critics question the use of devices and mathematical theory; they suspect that the use of tools may result from a lack of "natural" ability. Critics suggest that single-minded attention to conceptual and aesthetic aspects of art is more important than accuracy. The idea that artists are

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[31] Arnheim, *Thinking*, 19
[32] Kemp, *The Science of Art*, 105
[33] Mannoni, *Eyes*, 16

"cheating" when they use tools to create a convincing representation of the world is controversial even today. Optical devices and geometric systems are often flawed and difficult to use. They usually provide skewed or incomplete information about physical properties of the world. Mastering artistic tools might simply be a part mastering an artist's ancient and intricate craft. Mastery would allow the artist to make John Hamilton's distinction between the "sense of seeing" and the "art of seeing."[34]

Linear Perspective

Beginning with Brunelleschi's observations in the early 15th century, artists and scientists began to theorize and develop a system for mapping depth onto a two-dimensional surface. In 1435, Leon Battista Alberti developed a systematic way to construct a perspective painting, which he published in his treatise, *De Pictura* (On Painting).[35] By 1500, linear perspective was a commonly utilized artistic technique.[36] Artists found it to be a useful geometric method of representing depth in the natural world.

Linear perspective codifies a method of mapping a three-dimensional space onto a two-dimensional plane. Perspective rules mediate the behavior of lines in relation to each other. Parallel lines that lie perpendicular to the picture plane will converge to a "vanishing point", and equally-spaced lines parallel to the horizon appear closer together as they recede into infinity. An unknown number of perspective systems were developed and used by artists after Brunelleschi and Alberti's early musings. Some utilized multiple vanishing points and developed systems of foreshortening, but most versions share these fundamental tenets.

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[34] Kemp, *Science*, 151
[35] Kemp, *Science*, 21
[36] Kemp, *Science*, 7

Alberti developed a device to help implement his system. Today, it is often referred to as "Alberti's window," but in *De Picture*, it was described as a grid of parallel squares formed by thick threads. The grid would be placed at the location of the picture plane, and the artist could use the graph to help map out spatial relationships onto a canvas, on which he might have sketched a grid for reference. Alberti's window is difficult to use; the system breaks down if the artist changes his point of view as he draws because the figures will shift in relation to the square areas. This system of a "net" placed in front of a scene would later be used and modified by artists such as Leonardo da Vinci and Dürer.[37]

Both Alberti's window and perspective as a system are flawed. Brunelleschi immediately recognized that the illusion[38] of depth in a perspective drawing would fail except under specific viewing conditions. In an early perspective experiment, he painted the Baptistery of St. John and then set up the painting such that the viewer had to look through a hole and view the painting reflected in a mirror. This constricted the spectator's point of view such that it was same as the artist's point of view as he painted.[39] If the spectator were to see the painting from any other angle, the scene would appear distorted and perspective rules would fail to realistically convey depth. Additionally, the viewer was only able to see the painting with one eye under these conditions; binocular depth cues – such as the slight differences in light entering the two eyes as a result of their horizontal displacement – would not have been in conflict with the illusory depth.

Alberti practically ignores the anatomy of the eye and the physical nature of light in *De Pictura*, offering no proof that his system reflects inherent

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[37] Kemp, *Science*, 171
[38] Mannoni, *Eyes*, 18
[39] Kemp, *Science*, 13

properties of vision.[40] He bases his system on a pyramid, which converges to a single point in the eye. He posits that the 'extrinsic rays' make up the outlines of each form in the world, and the 'intrinsic rays' inside the pyramid "are responsible for recording the surface qualities of color, light, and shade, etc."[41] Leonardo da Vinci, however, discovered that the visual power of the pupil does not conform to the constraints of a pyramid converging to a single point and that "the Albertian pyramid is not, therefore, a physical reality."

Before his treatise *On the Eye*, which included his observations about the Albertian pyramid, Leonardo da Vinci utilized vanishing points and other linear perspective cues in *Last Supper*. However the painting includes a large number of ambiguities and contradictions that reflect da Vinci's awareness of the problems of perspective. Throughout his career, he studied many of these problems and attempted to develop techniques that would improve the system and disguise its flaws. Like Brunelleschi, he realized that unrestricted viewing conditions would allow for visual distortions of the painted scene.[42] While Brunelleschi mediated the viewpoint of his early experimental paintings by having spectators look through a peephole, Leonardo's paintings, like *Last Supper*, were viewed in a context that allowed for a variety of viewpoints. If the viewer's position were fairly distant, distortions could be minimized because a shift in position would result in a smaller shift in viewing angle. A small angle would allow the viewer to compensate for the skewed shape resulting from a changed picture plane.[43] However, binocular vision could not be accounted for by any perspective system; nor could the perceptual distortions caused by color and tone. "The more

[40] Kemp, *Science*, 23
[41] Kemp, *Science*, 22
[42] Kemp, *Science*, 50
[43] Vishwanath, D. (2005), Why pictures look right when viewed from the wrong place, *Nature Neuroscience*, 8.10, 1401-1411.

Leonardo studied the visual world, the more such problems or perception asserted themselves."[44]

Subsequentially, artists like Dürer and Raphael attempted to modify the method in order to improve upon or disguise the flaws of the system.[45] There is evidence of optical geometry in the paintings of major artists from throughout Europe ever since Brunelleschi. Peter Paul Rubens and Diego Velázquez are examples of painters who "possessed a profound sense of the intellectual foundations of their art," despite lacking the overt display of linear perspective that characterizes the work of some of their predecessors.[46]

However, fundamental problems like viewpoint and binocularity could never be completely eliminated. This problem was exacerbated by the fact that many perspective theorists focused more on the geometrical aspect of perspective (the ability to measure and think mathematically about composition) than on the physical aspect that dealt with the, perhaps more elusive, nature of vision.[47] Perspective was based too much in "knowing" and not enough in "seeing." Even in the 16th century, the lack of attention paid to non-geometric aspects of art was criticized. Frederigo Zuccaro believed that vision involved "a complex system of sense, fantasy imagination and rational speculation," which could not be satisfactorily represented by mathematical principles. In his 1766 treatise on perspective, Eustachio Zanotti discusses the inability of geometry to precisely mimic visual experience. However, he still supports perspective as a tool for realism by recommending rules of perspective as the best way to "situate an observer securely in three-dimensional space"[48] and to "evoke reality."[49]

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[44] Kemp, *Science*, 50
[45] Kemp, *Science*, 59
[46] Kemp, *Science*, 99
[47] Kemp, *Science*, 76
[48] Mannoni, *Eyes*, 17
[49] Kemp, *Science*, 142

Camera Obscura

Despite the long and rich history of linear perspective, lens based devices have been much more influential on modern artistic practices. The technology of lenses and mirrors has been a central interest of optical theorists since the days of Alhazen, and innovations in digital photography allow this powerful mode of representation to remain relevant to artists and scientists today.[50] The camera obscura was one of the first mechanized lens systems that influenced artists and allowed scientists to explore the idea of a simulated eye.

Essentially, the camera obscura is a lens and pinhole aperture system that allows light to pass through and refocus on a flat surface. In order for the transformed image to be visible, the room that contains the surface must be relatively dark – hence the word *obscura*. The system is a simple mechanical eye. The aperture is analogous to the pupil, the lens of the camera replaces the lens of the eye, and the dark room and flat surface are the interior of the eye and the retinal surface. Robert Hooke made the analogy of canvas and retina even stronger when he invented a version of the camera obscura that used a concave surface to enhance the focus of the image.[51] Improvements and specifications have been made from this basic framework, while retaining the essential aspects of lens and aperture.

The camera obscura was originally popular as an instrument of magic. Magicians would use it to “astonish and entertain the spectator.”[52] The aura of mystery surrounding the camera has survived to this day; stories have been written about its strange powers, including at least one murder mystery novella

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[50] Kemp, *Science*, 189.
[51] Kemp, *Science*, 190
[52] Kemp, *Science*, 191

that implicates da Vinci and Vermeer[53] and a romantic work of historical fiction involving the device.[54] Possibly, the instrument maintains this character because of the strange dichotomy between images as seen through the camera obscura and images as seen by the eye. "While the images one gazes upon are in fact actually happening only a few feet away, the experience of looking at the camera screen evokes feelings of solemnity and awe."[55]

But the camera obscura also found a place among the instruments of scientists and artists. Scientists viewed it as a physical model for the eye and experimented with different lenses and systems of mirrors to develop a deeper understanding of the role of optics and the retina in vision. Early 17th century artists, especially those in Holland who were working in a context that viewed art as a "direct and empirical form of representation," may have used the camera obscura to observe nature. They also used it as a direct tool for painting.[56] For both scientists and artists, the instrument could be used to simulate the image on the retina and to learn something about the information the brain uses in order to form a percept. If artists could master this simulation, they could create stultifying illusions of nature on the surface of a canvas.

Some artists, including Vermeer, most likely used the camera obscura directly and extensively. Evidence of Vermeer's use of the device comes from the presence of many of the visual characteristics of the projected image in his paintings. Normally, "we remain largely unconscious" of these aspects of color, tone, and scale that are emphasized by the camera obscura.[57] Canaletto is noted as a masterful Italian artist who most likely used the optical device in formulating his work. Direct evidence, in the form of writing, points to an intellectual interest

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[53] Knowles, *The Secrets of the Camera Obscura*
[54] Chevalier, *Girl with a Pearl Earring*
[55] Knowles, 14
[56] Kemp, *Science*, 193
[57] ibid

and involvement with the camera.[58] Evidence of the use of optical devices among other artists has arguably been understudied, and David Hockney has claimed that many more artists used optical devices than historians report.[59]

Despite the seemingly accurate representation of nature by the camera obscura, there are flaws in implementation. If the imaged surface of the camera obscura is the retina, that forces the artist and the observer into the role of the homunculus. The image is formed by light traveling through the aperature and lens, but it is again processed by the human eye and perceptual system. The device does not compensate for that. Rather it works on the assumption that if nature is translated onto a retina-like surface then the viewer will experience an image similar to what he would experience while viewing the natural scene. The problem is that the spectator never actually "sees" the image on the retina, and so to try to reproduce the retinal image on the surface inside a camera obscura will only yield further distortion.

Claude Glass

Like the camera obscure, the Claude Glass served to emphasize aspects of the visual world not normally recognized by the human perceptual system. Named after Claude Lorrain, whose paintings contained a rich color scale emphasizing middle tones, the Claude glass reflects an image considered to be more picturesque than the actual scene. The Claude glass is fundamentally a dark mirror. It was often convex in order to reflect a broad field on a small surface, but at the height of its popularity, it came in a variety of shapes. The dark backing or "self-tinting" reduced highlights in the scene and allowed "the subtlety of the middle tones to emerge."[60] The narrower range of tones reflected by the Claude

[58] Kemp, *Science*, 196
[59] Hockney, *Secret Knowledge*, 12
[60] Kemp, *Science*, 199

Glass allowed the artist to more directly transpose the colors in the scene into paint and to convey a pleasing atmospheric affect of "warm brown" in the foreground and "cool, silvery blue" in the distance.[61]

The glass works by shifting the color spectrum in a non-systematic or predictable way. The user does not have control, and it is much less mechanical than either the perspective system or the camera obscura. As a result, it is both appealing to artists because of its lack of "artlessness" and unappealing because it required very little effort or skill. In fact, the Claude Glass was quite popular with tourists as a way of creating "harmonizing effects" with scenic landmarks.[62] While perspective systems and the camera obscura likened the artist to a scientist, the Claude Glass reemphasized the subjective role of the artist as an aesthetician.

Photography

The photographic camera, in both its analog and digital manifestations, is by far the most common optical device being used today. Unlike the other tools we have discussed, the camera serves both as its own medium and as a simulated eye. In fact, it is an evolved form of the camera obscura. Early efforts by Niépce and Daguerre to fix an image on a surface utilized the preexisting system. The modern camera retains the basic lens and aperture structure, but it also stores the image, either in the form of digitally coded pixels or as a transparent negative.

The history of photography is well studied and documented. Various methods of recording an image onto a surface were developed before film negatives became the standard. Joseph Niépce studied light-sensitive surfaces, and, after achieving a fixed image on a copper plate coated with asphaltum in 1822, he collaborated with Louis Daguerre. Daguerre's process, which involved iodized silver plates treated with mercury vapors, would be credited in France as

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[61] Gombrich, 40
[62] Kemp, *Science*, 199

the first successful photographic process. However, it was William Henry Fox Talbot who, by 1835, invented a method of recording images on paper, and it is his process that survives today in the form of the negative.[63]

Photography has served as a way to enhance understanding of optics and vision in general, and it has also been utilized as a tool to expand our visual language by translating physical information into a visually comprehensible form. Notably, photography has helped humans comprehend motion and light. The experiments of Edward Muybridge allowed scientists and artists to understand biological motion to an extent impossible with the naked eye.

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[63] Kemp, *Science*, 218

Color

Color is a visual quality that only exists through perception. Although the motion of a light particle can be characterized by its wavelength, and surfaces tend to reflect certain wavelengths and absorb others, objects do not 'possess' color. Rather, the experience of color is dependent on light and the brain; the visual system creates a percept to represent light and surface properties. To clarify the point, compare the concept of color with that of shape. The shape of a solid, rigid object is independent of its position in space and the amount light in its environment. Additionally, we tend to believe that shape characterizes an object even when there is no one to touch or see it. On the other hand, color is dependent on all of the qualities listed. If an object changes position, surfaces change color, and if the illuminant changes, the color of the object will change as well. Further, the visual system is necessary. Color results from the combination of illuminant and surface properties, and without the visual system, there is no mechanism to combine these properties into a meaningful quality. Yet this quality is often intangible and unpredictable relative to "even our shifting perceptions and representations of space," which "seem positively stable and consistent when compared to the elusiveness of color vision."[64]

The idea of a percept being distinct from physical information can be illuminated by a common philosophical thought experiment called "Mary's Room." The scenario asks us to imagine a woman named Mary who has never experienced color. She grew up in a black and white room and everything from her books to her food were gray. Ironically, she devotes her life to studying color perception, and she comes to know everything about color, optics, and the brain. Finally, she goes outside and sees a rose. Having known everything about the

[64] Kemp, *Science*, 261

color red will she learn anything new by seeing the color first hand? Frank Jackson used this story to argue that there is more to perception than knowledge of physical information. Despite her infinite grasp of the properties of sunlight and the surface of a rose petal, she never utilized the perceptual mechanism to combine these properties in a meaningful way until she stepped outside. Without having seen red, "her previous knowledge was incomplete." [65]

The elusiveness and complexity of color have obsessed scientists, and the emotional effect and symbolic salience have fascinated artists. Both are important aspects of the phenomenon, and as a result, scientists and artists have influenced each other's theories and practices. The French chemist, Chevreul, supervised the preparation of dyes, and he observed the affects of interactions between juxtaposed pigments. From his observations, he published the "law of simultaneous contrast," which defined different situations in which colors affect each other's appearance. Like Josef Albers, he discussed a variety of effects and tried to prove that

> the painter or designer must strive to disentangle these effects. Above all, the 'law of simultaneous contrast' was designed to show how an artist's perception of color may be distorted, and how these distortions could be circumvented. If a grey surface appears to be tinted violet under the influence of an adjacent yellow, the painter should be aware that it is actually grey and paint it as such.

Chevreul sought to educate artists about the interaction of color, which he had gained from experience with pigments. However, Chevreul's understanding of perception was limited. In fact, Alber's discussion of the Weber-Fechner Law was a direct response to instructions for creating a linear gradient written by Chevreul that did not take perceptual compression of intensities into account.

Despite his emphasis on perceptual theory, Chevreul still believed that "artistic intuition remained ultimately supreme in the composing of a great work

[65] Jackson, Epiphenomenal Qualia, 130

of art." The artist should be aware of the nature of perception in relation to the world, but he should not attempt to demonstrate harmony of color and composition through formulas or theoretical knowledge.[66] This attitude was advocated by the artist Delacroix, who may have attended Chevreul's lectures and read his theories. His paintings utilize some of the concepts that Chevreul had written about, but he breaks the rules when necessary for artistic efficacy.[67]

[66] Kemp, *Science*, 307
[67] Kemp, *Science*, 310

Experiment

Abstract

This research project attempts to quantify the subjective quality of color vision that artists like Josef Albers have explored through their art. It is widely understood by artists and scientists that the appearance of a surface color is affected by its context. However, there are many questions yet to be answered about the specific spatial relationships between colors. This experiment uses an achromatic adjustment task to compare the context effect of colors inside and outside of a grid containing a test square. The results show that the color inside the grid has a greater affect on the appearance of the test square than the color outside the grid. This result was found across observers without exception. The idea that colors affect each other more when placed closer together may seem intuitive, but our results serve to confirm this assumption and to set the groundwork for further studies to develop a general theory of color interaction.

Methods

Stimuli

The stimulus was a 3 by 3 grid of approximately 1.5 inch squares with a black border around each (**fig. 3**). The grid was created in Adobe Illustrator© with squares filled with the color defined by [0 0 0 76] in CMYK coordinates. The grid was printed with an Epson Stylus Photo R300 printer and mounted on flat board. The black borders were covered with velveteen to minimize the amount of light reflected off of the surface. The board was attached to a rod that fit into a hole in a large white board and slid back into a set position, such that the grid was positioned approximately three inches in front of a large white background.

A projector was mounted in front of the grid with a slanted mirror to shine light directly onto the grid and board. We used a computer to control the projector such that it could shine light on any part of the set up; the squares could be illuminated independently of each other and of the background. As a result, any pattern of lights and colors could be projected onto the grid. This allowed us to use just one grid rather than print grids of many different colors and patterns. We choose 2 test colors based on their ubiquity in natural scenes. The neutral color was defined as the average of the test colors. The test and neutral colors were projected onto the grid and background.

Task

Observers viewed the grid through a large aperture while sitting in a booth. The grid, background, and walls of the apparatus were visible, but the projector was not. The background and the squares of the grid were illuminated with one of two test colors or with the neutral color, which was the average of the test colors. Each square in the grid was illuminated with the same color, but the luminance of each square was randomly modulated. The center square (row 2, column 2) was illuminated with the same color as the other grid squares (**fig. 4**).

The task of the observers was to perform an achromatic adjustment of the center square. Even though the center square was illuminated with a similar color as the other squares, the observer could press a button to flash the current match color for 0.5 seconds. This color was chosen randomly at the beginning of each trial. The observer used a joystick to adjust this color in a red-green, blue-yellow coordinate system. The current match color was also flashed every time an adjustment was made.

Observers were instructed to make the flashed color appear gray. Specifically, they were told it should look neither blue nor yellow and neither green nor red. When observers were satisfied with this condition, they could confirm their match. Then, the aperture closed, new colors were projected, and the aperture was opened for a new trial. There were 9 trials in each session to allow for each combination of test and neutral colors on the grid and the background. Each observer ran 3 sessions.

Results

Achromatic adjustment tasks tend to provide consistent and reliable results when attempting to gage color perception. We found that this task yielded data reflective of perceptual experience because observers' settings for grey depended on the surrounding colors in the grid and in the background. In other words, different color settings looked the same (grey) to observers because of the context.

4 observers ran 3 sessions each. 2 observers were naïve, and 2 were privy to the details of the experiment (the author and her advisor). The color setting was converted into xyY coordinates for analysis, where x and y are sufficient to represent the hue and saturation of the setting, and Y is defined as the luminance of the setting. We plotted observers' settings for each trial type (each combination of test and neutral colors on the grid and background) on a y vs. x grid. Data points are averaged over all 3 sessions (**figs. 5a-d**).

All subjects were able to perform the task reasonably well, although it was fairly difficult for one naïve observer (**fig. 5d**). This observer's match settings were inconsistent from session to session, yielding large error bars. Generally, illuminating the grid and the background with the same test color caused the observer's grey setting to shift towards that color. In other words, the color that observers perceived as grey actually contained some of the color of the illuminant. Illuminating the grid with a test color and the background with the neutral color tended to have a similar, but smaller effect. Illuminating the background with a test color and the grid with a neutral color yielded an even smaller effect (**figs. 5a-d**).

An interesting condition is that in which the color of the background and the color of the grid conflict with each other. Neither is neutral, so they might both interact with the appearance of the test square. We found that generally, both the grid color and the background color have an effect on the appearance of the test square; the setting for this condition tended to be somewhere in between the setting for the grid color with a neutral background and the setting for the background color with a neutral grid. However, the effect of the grid color was much larger, and the setting for conflicting colors was generally closer to that of the grid color than that of the background color.

In order to compare the effect of the grid (the inside) and the background (the outside), we created a more quantitative measurement of the effects by calculating the distance between settings. The *outside effect* was calculated by taking the average of the distances between settings for a neutral background and those for a background illuminated by a test color. Similarly, the *inside effect* was calculated by taking the average of the distances between settings for a neutral grid illuminant and those for a grid illuminated by a test color. We plotted the inside and outside effect for each observer (**fig. 6**). Without exception, the effect of the inside color illuminating the grid was much larger than that of the outside color illuminating the background.

Discussion

Although Albers established that surrounding a color with a ground affects the appearance of the color, he did not speculate as to why visual processes would produce such an effect. One theory is that the perceptual system tries to estimate the local and global illuminants of a scene. Nearby objects are usually illuminated by the same source. If this is the case, the perceptual system's estimate of the illuminant of a surface may be impacted by the estimate of the illuminant on the surrounding surfaces. Our results are consistent with this theory. The illuminant of the test square may be estimated to be more similar to the illuminant of the grid than to the illuminant of the background. Additionally, one might think that as an illuminant covers a larger portion of the visual field, it will be more likely to be interpreted as the global illuminant of the scene. This theory is also consistent with our results; when the same color was projected onto the grid and the background, the effect on the appearance of the test square was larger than if either the grid or the background were illuminated by the neutral color.

Another theory is that the visual system emphasizes chromatic edges as it does luminance edges. It is well known that the receptive field shape of neurons in the early stages of visual processing causes the system to increase the perceptual contrast of a sharp jump in intensity in relation to the physical contrast. In other words, the dark side of an edge is made to appear darker, and the light side is made to appear lighter. This effect can be illustrated by the Mach Band illusion (**fig. 7**). Each band is one solid color, but they each appear darker on the left side and lighter on the right.

It may be possible that changes in color are emphasized over edges as well. If this were the case, color changes would probably be based on Hering's Opponent Process Theory, which states that colors are processed in red-green, blue-yellow, and black-white channels. Albers observed that as one adds yellow to a color, it becomes less blue and visa versa. Similarly, colors juxtaposed with yellow would appear bluer at their edges, and colors juxtaposed with red would appear greener at their edges. This is not hard to believe because the shape of the receptive fields of color sensitive neurons in the early stages of processing is similar to that of non-color sensitive neurons.

The fact that the grid color had a large effect on the appearance of the test square might be accounted for by this theory. The test square was fairly small, and if all four of its edges were made to appear more like the opponent color of the grid illuminant, it might affect the appearance of the entire square. This is a possibility; Albers observed that a color could be simultaneously affected by influences in many directions.[68] However, with this theory it is less plausible that the background illuminant would affect the appearance of the test square or even the grid. The test square shared no edges with the background, and only one or two edges of each grid square were juxtaposed with the background.

Clearly, much more research can be done in to develop a theory explaining the spatial aspect of color interactions. I have laid out some ideas, but reasons for the effect should be tested formally. Additionally, a full theory would require testing different size grids to find out how the magnitude of the effect is changed as the grid field size gets smaller or larger. It would also require testing a larger set of test colors – here we used only two. Albers discovered through his searches that certain colors are more susceptible to change than others. He advised his students to explore colors in order to find the ones that are more likely to be influenced and the ones that are more likely to be influenced.[69] It is possible that we chose colors that are not typical in their propensity to change or be changed. Mapping out the color pairs that yield the smallest and the largest effects might yield some interesting facts about this issue. Another issue is that of lightness and hue. This experiment explored the effect of color juxtapositions on the appearance of hue, but the appearance of lightness was ignored. For a more complete theory, this factor should be taken into account.

Many questions have yet to be answered, but this experiment begins to develop the framework within which to ask them. The apparatus used here could easily be adapted for a variety of experiments exploring all of the issues that I have touched upon. Ultimately, the qualitative theory developed by Albers

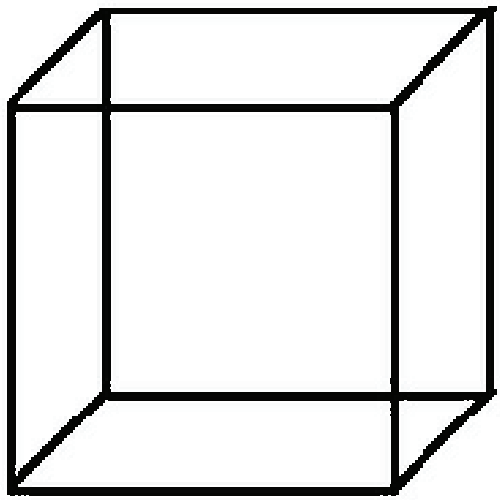
[68] Albers, 11

[69] Albers, 9

through trial and error can be quantified and confirmed through studies like this one. Hopefully, a full understanding of the neural mechanisms causing these effects will be obtained as well.

Figure 1

a.



b.

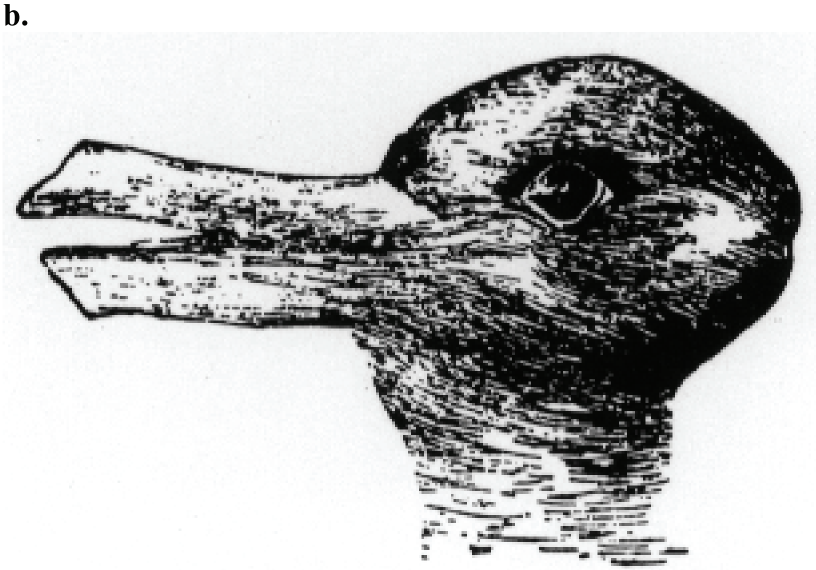


Figure 2

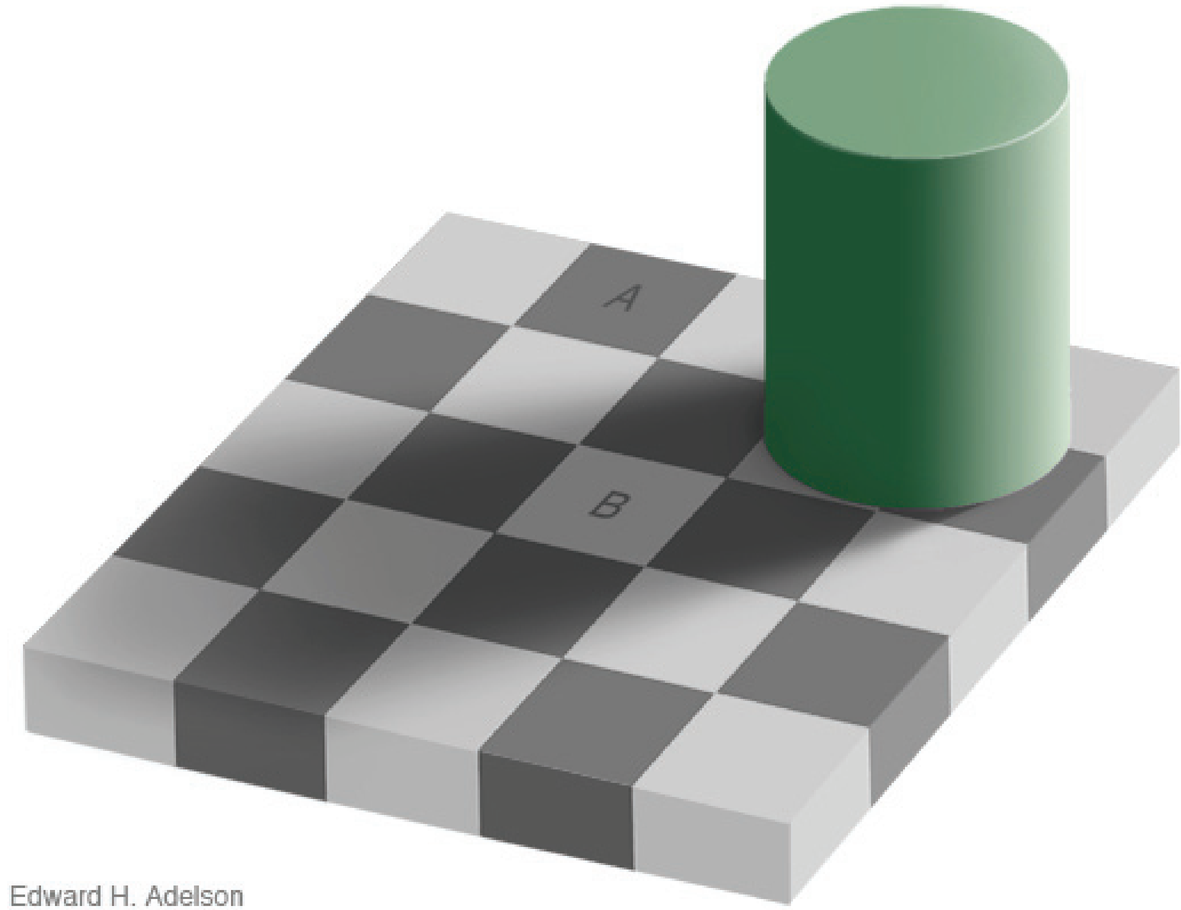


Figure 3

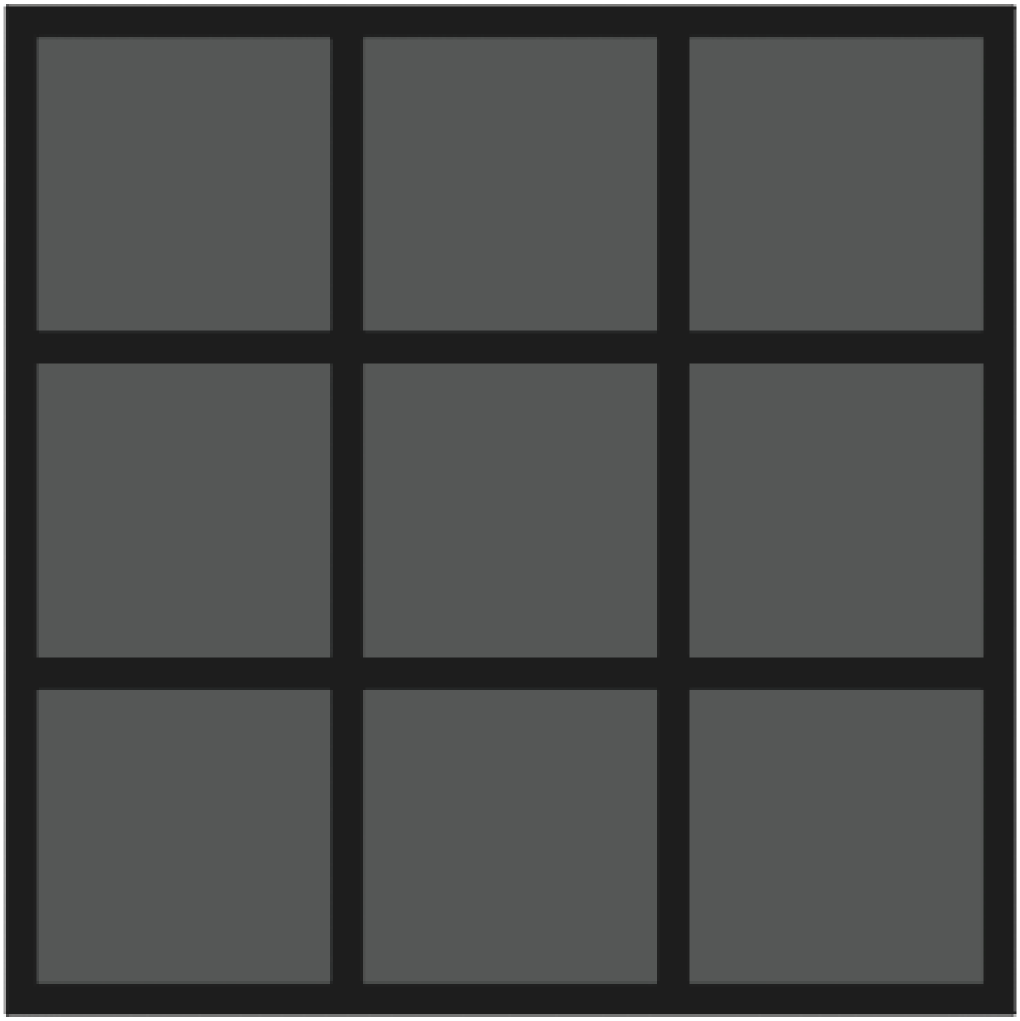


Figure 4

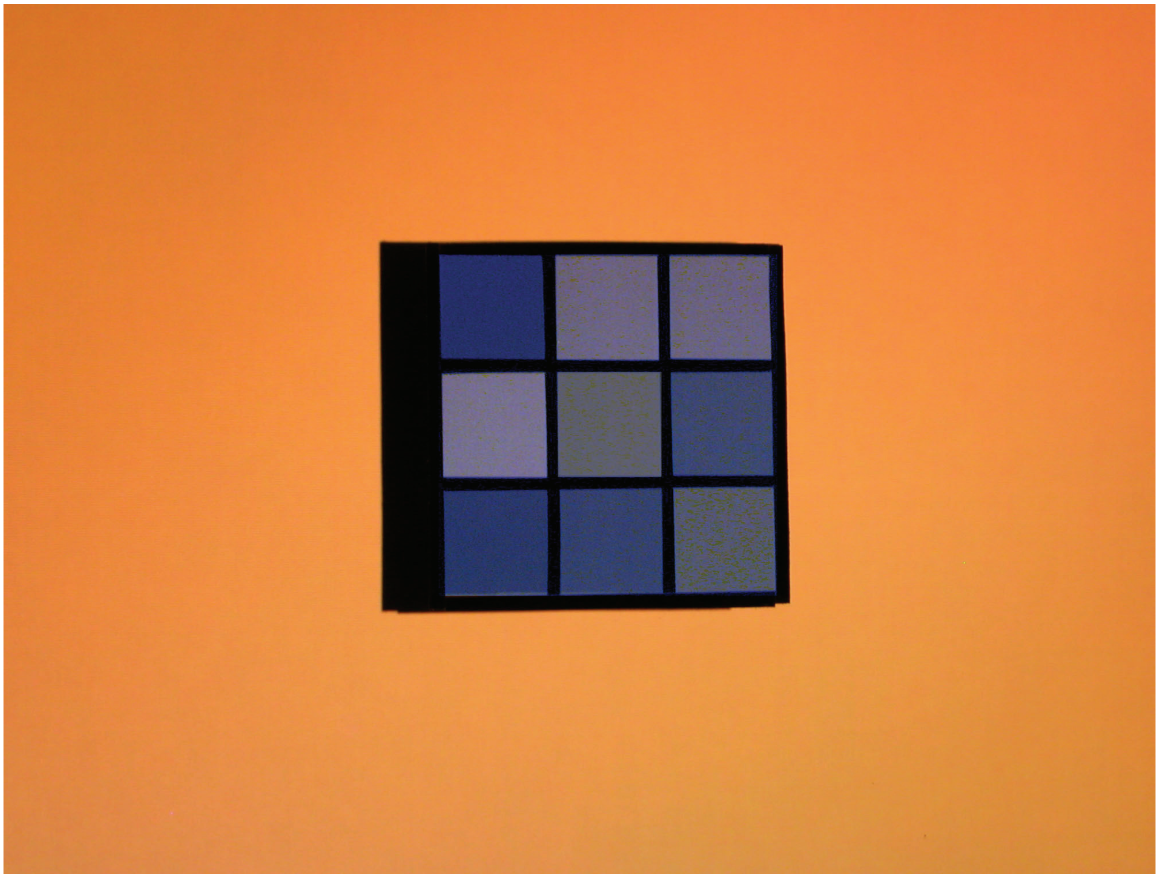
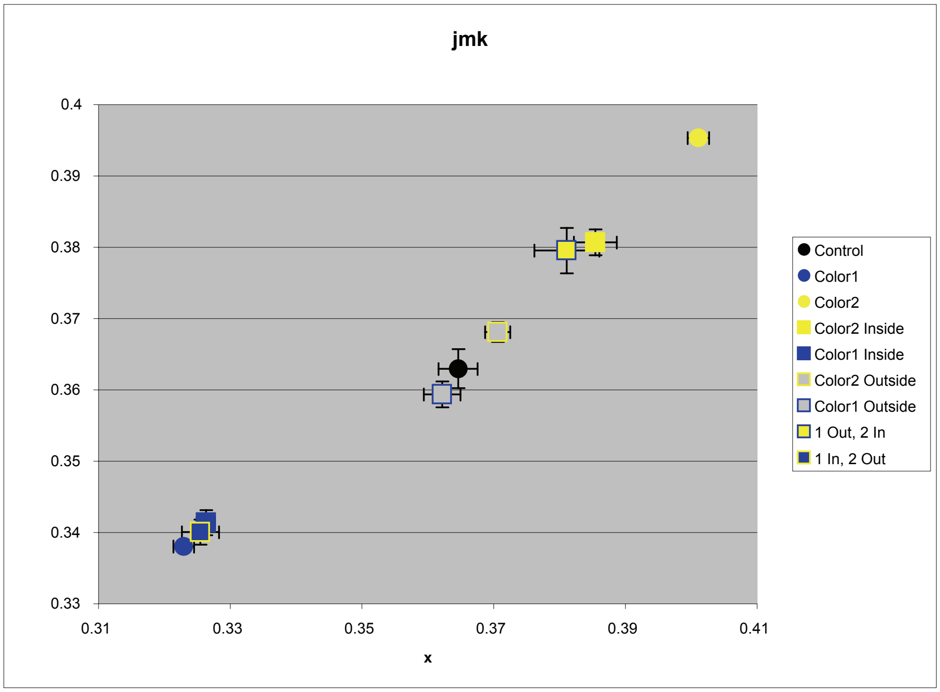


Figure 5

a.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0.33
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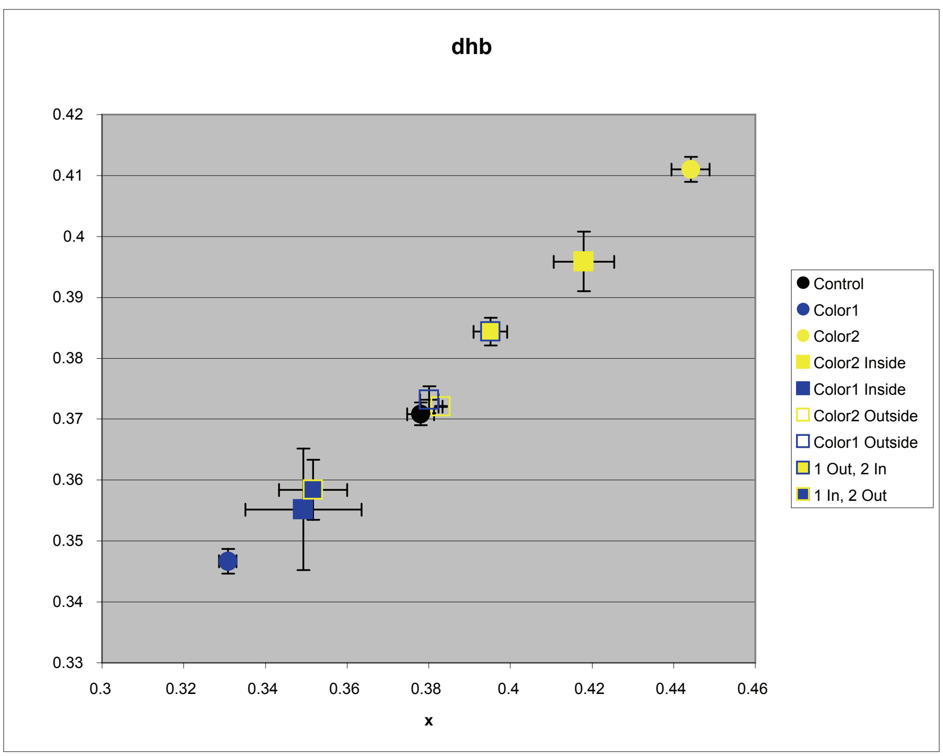
0.33
0.35
0.37
0.39
0.41
x
Control
Color1
Color2
Color2 Inside
Color1 Inside
Color2 Outside
Color1 Outside
1 Out, 2 In
1 In, 2 Out

b.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0.34
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0.38
0.4
0.42
0.44
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Control
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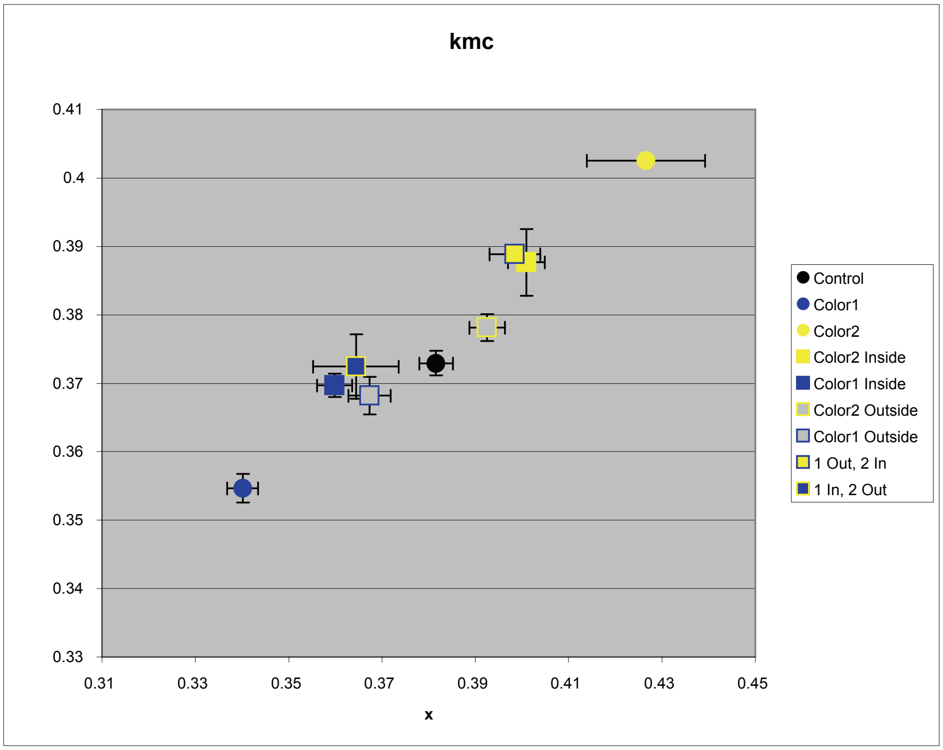
Color2
Color2 Inside
Color1 Inside
Color2 Outside
Color1 Outside
1 Out, 2 In
1 In, 2 Out

c.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0.37
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0.41
0.43
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x
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Color2
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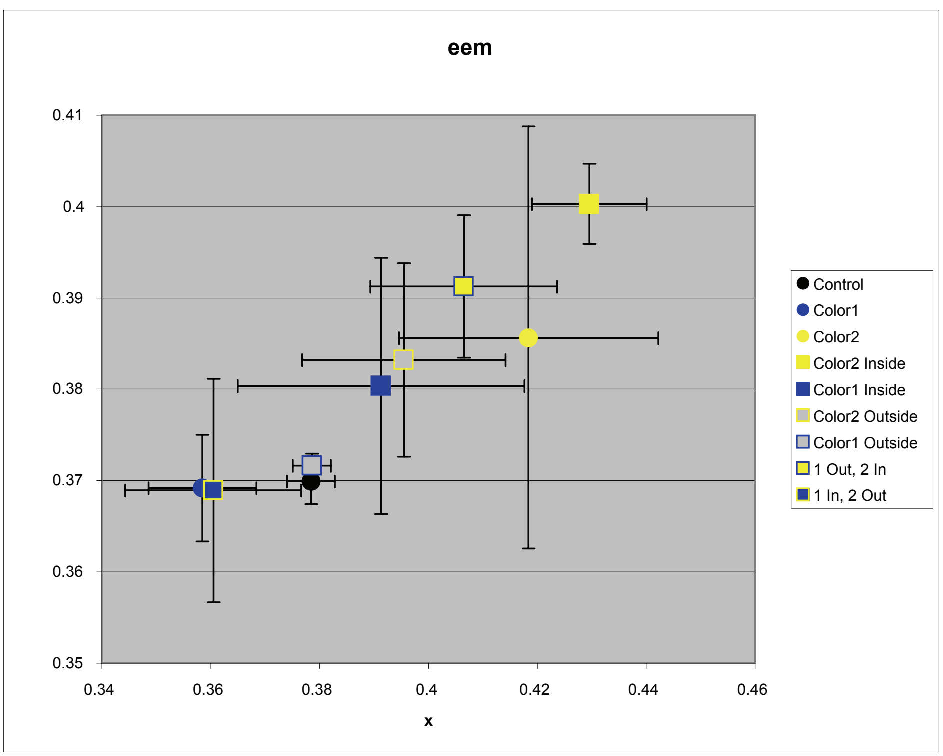
Color1 Inside
Color2 Outside
Color1 Outside
1 Out, 2 In
1 In, 2 Out

d.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0.42
0.44
0.46
x
Control
Color1
Color2
Color2 Inside
Color1 Inside
Color2 Outside
Color1 Outside
1 Out, 2 In
1 In, 2 Out

Figure 6

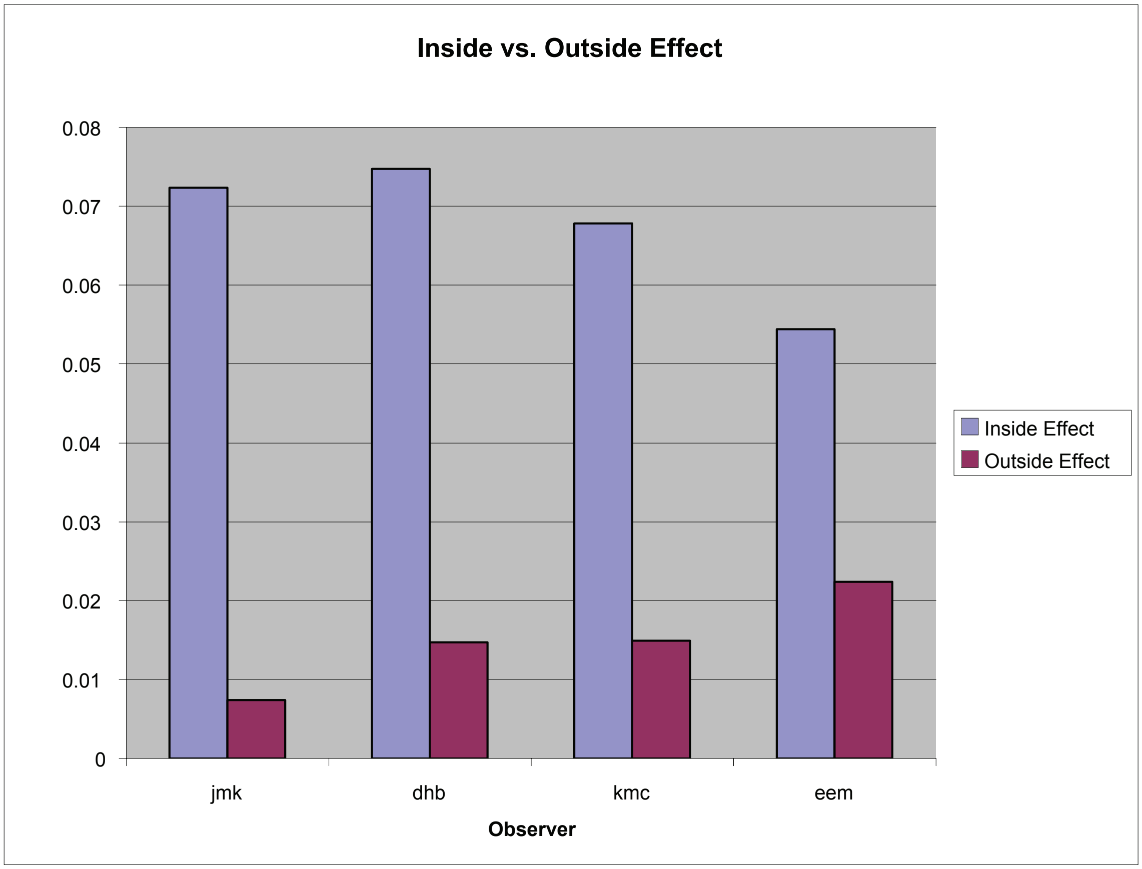
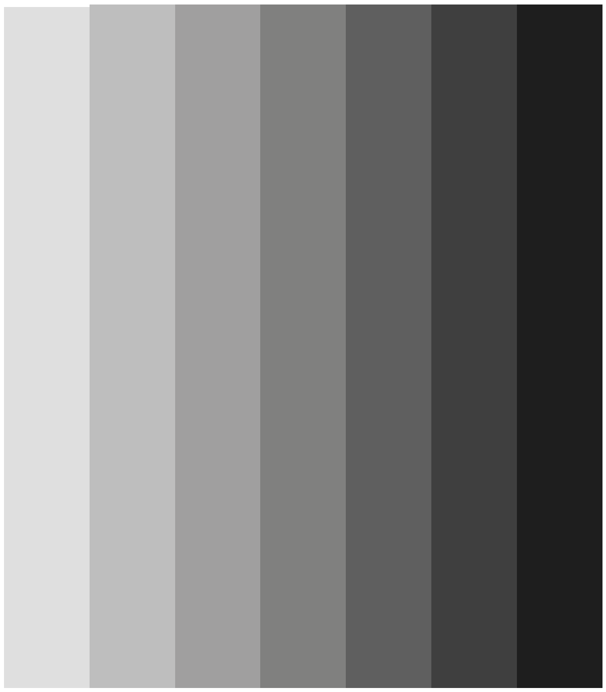

Inside vs. Outside Effect
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
jmk
dhb
kmc
eem
Observer
Inside Effect
Outside Effect

Figure 7



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