EXAMINING THE EFFECT OF CONTEXT ON THE WATERCOLOR ILLUSION

by

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ABSTRACT

The watercolor illusion (WCI) occurs when a physically non-colored region surrounded by an outer contour and an inner fringe appears filled in with a pale tint the same hue as the fringe (see Figures 2 and 3). Previous literature investigating the WCI has focused primarily on stimulus parameters affecting illusion magnitude and the likely neural mechanisms responsible, rarely discussing how this phenomenon may be affected by global context. The present experiments are the first to explore the effect of global context on the WCI. Experiment 1 examined the WCI using pictures of a variety of three-dimensional solid surfaces and objects as compared to more traditional two-dimensional stimuli. By keeping the local information nearly identical across conditions we evaluated how the global context influenced the magnitude and spatial extent of the illusion. Experiment 2 examined the influence of global context further using images of three-dimensional wireframe versions of the solid looking objects used in Experiment 1. Experiment 3 examined how the perception of WCI stimuli were affected when split into two parts. This allowed us to explore how global stimulus changes impact color spreading as it relates to previous literature showing the WCI spreads in the absence of a border. The fact color failed to spread outside of these now physically unenclosed configurations demonstrates global configuration is an important factor in how color spreading manifests. This study is one of the first to demonstrate the global configuration of WCI stimuli can influence color spreading and color spreading may not occur with unenclosed stimuli depending on this global context.

INDEX WORDS: Watercolor Illusion, Color Spreading, Context, Perception

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CHAPTER 1

COLOR SPREADING ILLUSIONS

"The brain didn't evolve to see the world the way it is. We can't. Instead the brain evolved the way it was useful to see in the past…" (Lotto, 2009). Visual illusions by their very nature are alluring and mesmerizing – even to those outside the field of perception. Their variety is innumerable, and their contradiction to our normal visual experience can make them seem surreal. In perceptual research, illusions can play an important role by shedding light on the limitations and ultimately the functionality of the human visual system. For instance, the Hermann grid gives the impression of black smudges at the intersections of white bars when viewing the intersections parafoveally; however foveal viewing of these intersections reveals that no such smudges exist. This illusion was originally believed to occur due to lateral inhibition, a process by which neighboring neurons can affect the activity of one another due to receptive field interaction (Baumgartner, 1960). As receptive fields are larger parafoveally, this was a logical assumption. More recently however, researchers have suggested that S1 type simple cells in the primary visual cortex are more likely to be the mechanism for perceiving this illusion (Schiller & Carvey, 2005).

Some illusions require a more complex explanation than the Hermann grid. This is true for a variety of reasons. First, the Herman grid is a fairly low level visual phenomenon (albeit higher than previously believed based on current research). Illusions involving higher level visual processing and cognition such as those related to depth or illumination are going to likely be the perceptual byproduct of many cortical processes along the ventral pathway in conjunction with other cognitive processes (e.g., memory, expectation). As visual system development is dependent on proper environmental exposure (e.g., Blakemore & Cooper, 1970), it is unsurprising that even the environment in which our visual system developed can play a substantial role in the perception or magnitude of an illusion (Brislin & Keating, 1976; McCauley & Henrich, 2006). Despite the complexity of the mechanisms required to perceive visual illusions, they are all the byproduct of the structure (and perhaps limitations) of the human visual system and are therefore indicative of the structure therein.

Illusions themselves are typically stimuli that we are unlikely to see in our day to day lives. For instance, we are unlikely to observe a Hermann-grid-like stimulus while driving to work or walking down the street. Many illusions "trick" our visual system by pushing some mechanism to the point at which its limits are noticeable. Some illusions are simply the byproduct of some combination of processes within our visual system. For example, the Hermann grid illusion does not provide our visual system any specific advantage. Instead, we perceive the Hermann grid simply as a byproduct of our normal visual processing. However, other illusions are likely manifestations of useful and necessary heuristics the visual system implements to increase the speed and accuracy of information being processed in our visual environment. For instance, both the Müller-Lyer and Ponzo illusions can be explained by looking at how normal depth perception occurs. Most straight contours in your visual field are actually parallel or intersecting at 90° angles (e.g., walls, roads, table tops) rather than the acute or obtuse angles that contribute to linear perspective in our visual field. Although these contours reach our retinas at various angles, we tend to perceive a depthful carpentered environment instead. The notion that these illusions exist due to a depth perception heuristic is further supported by a drastic reduction in illusion magnitude for both of these illusions in individuals living in non-carpentered environments (Brislin & Keating, 1976; McCauley & Henrich, 2006).

Although not a visual illusion, another visual phenomenon known as boundary extension can start our discussion on how identifying and understanding the limitations of the human visual system can help us better understand the underlying processes producing our normal visual experience. When asked to recall a previously viewed scene people tend to recall more of the scene than was actually present at study (Intraub & Richardson, 1989). This error of commission known as boundary extension is the byproduct of another heuristic implemented by our visual system. The human visual field is limited by the forward facing nature of our eyes and also by other factors such as occlusion. Therefore it is necessary we look around often and create an egocentric representation of the world. Boundary extension is supporting evidence of this internal representation and its subconscious predictive nature. By understanding that visual illusions and "errors" are often only byproducts of the heuristics, limitations, and general functionality of our visual system, we can assess the mechanisms and examine the ecological validity of other visual illusions similarly.

A subclass of visual illusions exists in which a physically present colored portion of a stimulus can perceptually spread beyond its physical boundary. Neon color spreading (NCS) is likely the most well-known and most researched of these color spreading illusions; however there are a few others including the discoloration illusion (Pinna, 2006), the backlighting illusion (Pinna & Reeves, 2006), and the watercolor illusion (WCI) which is the primary focus of the following research. It is important to understand the theories, models, and potential differences between these illusions first however to better understand and interpret what the WCI means for the human visual system.

NCS was first demonstrated using a lattice of uniformly colored contours with a "subpattern" of the contours consisting of a different color. This change in hue generates an impression that the lattice is illuminated from some source similar to the subpattern color in the regions surrounding the lattice where no color is actually present which then ceases to exist at the boundary of the subpattern color change (Tuijl, 1975; Tuijl & Leeuwenberg, 1979) (see Figure 1A). This effect is greatly reduced or eliminated if only the subpattern exists however, thus highlighting the importance of global configuration in color spreading illusions (see Figure 1B). Phenomenologically NCS has two basic properties: coloration (the impression of illumination Tuijl described) and figural effects (Pinna & Grossberg, 2005). The neon-like color ceases at the boundary of the subpattern. This creates the perception of a neon figure with sharp borders similar to an illusory contour (Tuijl & Leeuwenberg, 1979). A study by Watanabe and Sato (1989) demonstrated however that NCS and illusory contours are governed by separate mechanisms demonstrating that one can be removed while the other persists. Nonetheless, the figural nature of NCS is phenomenally and semantically similar to illusory contours and surfaces as neither are physically present despite their convincingly distinct impression.

In a similar fashion to NCS, the WCI is a color spreading illusion that occurs when a shape has a contrasting inner and outer border; this generates a perceptual filling-in of the center of the shape with a hue similar to the inner border which is often referred to as the “fringe” (Pinna, Brelstatt, & Spillmann, 2001; see Figure 2A and 2B). These stimulus parameters are quite different than NCS. As such the perception of the color spreading region is also different. For instance, in NCS the color that appears to spread seems to be a transparent film covering a defined region. In the WCI however the color spreading region appears to be an opaque solid (Pinna & Grossberg, 2005). As with NCS, the color inducing portion of the stimulus is not enough by itself to generate the illusory spreading (see Figure 2C and 2D) which again highlights the importance of global configuration in these illusions.

Pinna and colleagues (2001) examined a number of parameters to determine what conditions are necessary to induce the WCI and what conditions render the greatest illusion magnitude. For instance, the illusion was shown to dissipate substantially beyond 45º of visual angle suggesting there is a maximum range across which the color can spread. Additionally the illusion magnitude decreased as the border contour thickness increased with an optimal contour thickness of 6' of visual angle. The borders of WCI stimuli are often wavy or scalloped. This shortens the distance between certain points along the inside of the shape which helps to magnify the illusion. Pinna and colleagues (2001) note that "…the strength of color spreading increases monotonically with increasing spatial frequency of the sinusoidal modulation" (p. 2671) even though stimuli with straight borders produced substantial (albeit weaker) illusion magnitudes. The colors and relative luminance of the inner and outer borders are also relevant to the strength of the illusion. While most combinations of colors and contrasts produce at least a modest spreading effect, the greatest illusion magnitudes are reported for stimuli with high contrast between the inner and outer border in regard to both color and luminance (Devinck, Delahunt, Hardy, Spillmann, & Werner, 2005). Stimuli with a blue or purple outer border and a yellow or orange inner border elicit the most vibrant spreading. Under these optimal conditions, the WCI is easily observable in as short a duration as 100 ms suggesting an instantaneous unconscious color spreading mechanism. A similar watercolor effect has even been observed achromatically suggesting color is not required for a similar perceptual spreading phenomenon to occur and that chromatic aberrations cannot solely account for their existence (Cao, Yazdanbakhsh, & Mingolla, 2011; Pinna, 2006). Both the WCI and NCS stimuli are typically shown on white backgrounds as the illusion magnitude is greatest in this configuration; however color spreading can occur to some degree on any background color including black (Pinna et al., 2001).

This spreading effect seems to be processed first locally then globally as demonstrated by equal illusion magnitude for dotted and solid contours (Broerse & O'Shea, 1994; Pinna et al., 2001; Pinna & Grossberg, 2005) and by an increased illusion magnitude for wavier contours. The spacing between inner and outer contours is also relevant. When an interspace exists between the inner and outer contours, illusion magnitude decreases at a rate dependent on the size of the interspace (Devinck & Spillmann, 2009). Additionally, increasing lateral spacing of dots in dotted contours (rather than traditional solid contours) also decreases illusion magnitude. This highlights the necessity of certain local factors within the stimulus in generating a more global surface color spreading. The WCI is the strongest when the inner and outer contours are spatially contiguous and continuous. The colored surface perceived spreads from these local features, remaining constant across the entirety of the WCI region (Pinna et al., 2001). For example, an orange opaque surface perceived to extend from one inner contour across space to an adjacent inner contour appears phenomenally to be constant. The luminance contrast between the inner and outer contours can also directly affect illusion magnitude (Devinck et al., 2005). Achieving long-range color spreading is therefore going to be mediated at least in part by luminance-dependent mechanisms. Color spreading has even been shown to be achievable in the form of a WCI afterimage similar afterimages experienced after viewing a real colored surface (Hazenberg & Lier, 2013). These color spreading afterimages were highly dependent on luminance contrast – potentially more so than typical color spreading stimuli.

An additional phenomenological effect exists related to the WCI which echoes a similar facet of NCS. The spreading region in NCS generates a figure defined by an illusory colored border. In WCI stimuli, the border is physically present so no illusory figure needs to be generated. Nevertheless the WCI exhibits a unique figure-ground effect (including an associated effect known as the object-hole effect; Pinna & Tanca, 2008) somewhat similar to Gestalt cues of figure-ground organization (Pinna, 2005; Pinna & Reeves, 2006; Pinna, Werner, & Spillmann, 2003; von der Heydt & Pierson, 2006). An enclosed WCI region tends to be perceptually organized as a figure; however this cue is often stronger than many figure-ground cues including grouping/proximity, symmetry, convexity, surroundedness, parallelism, closure, similarity (Pinna, 2005; Pinna et al., 2001; Pinna et al., 2003), good continuation, convexity, amodal completion, and past experience (Pinna et al., 2003). The object-hole effect described by Pinna and Tanca (2008) refers to the WCI's ability to switch an enclosed region of a stimulus from an opaque figural surface to an apparent hole in that surface thus rendering a more three-dimensional interpretation of a two-dimensional stimulus. This same literature regarding the object-hole effect posits that the opaque substantive nature of a WCI region creates a perception of three-dimensionality even without a "hole". These holes are dependent on the direction of color spreading caused by the illusion. Due to the powerful nature of color spreading in the WCI as a cue for figural status, any region surrounded by this "figure" into which color fails to spread tends to be perceived as a hole in this surface. An exception to this happens if the "hole" region moves around temporally on the WCI region, shifting the figure-ground organization of the stimulus to become its own figure in front of or on top of the WCI region (Tanca, Grossberg, & Pinna, 2010).

Additionally, psychophysical evidence supporting the existence of separate mechanisms responsible for generating the coloration and the figure-ground effects associated with the WCI (see Pinna and Reeves, 2006). These mechanisms responsible for color spreading and "figurality" (i.e., bias towards an apparent solid with figural status observed in the figure-ground effect) in color spreading illusions can possibly be explained by the FAÇADE theory which gets its name from the parallel but related neural mechanisms responsible for Form-And-Color-And-DEpth (Grossberg, 1997). For the WCI, the figural component is related to form processing, the color spreading component is related to surface processing, and the depth component is related to the organization of the WCI surface as figure against a ground whether it has a raised appearance or has holes in it (Bertamini, 2006; Pinna & Tanca, 2008; Zweig, Zurawel, Shapley, & Slovin, 2015). According to FAÇADE theory, cortical interblob regions are responsible for boundary grouping (i.e., border ownership leading eventually to figurality) whereas blob regions are responsible for filling-in processes (i.e., color spreading). Grossberg (1997, 2016) and colleagues (Grossberg & Mingolla, 1985) define the mechanisms underlying these processes as the Boundary Contour System (BCS) and Feature Contour System (FCS), respectively. These systems are thought to operate within the primary visual cortex and ventral extrastriate cortex from V2 to V4 (Grossberg, 2014).

In contrast, the LAMINART model suggests perceptual borders form within visual cortex laminar circuits (Grossberg, 1999, 2003b; Raizada & Grossberg, 2003). The name LAMINART is a conjunction between "laminar" which refers to the specific processing circuitry within the visual system described in the model and its inclusion of Adaptive Resonance Theory (ART) (Raizada & Grossberg, 2003). This model seeks to clarify how BCS operations are carried out by identical cortical circuits (Grossberg & Yazdanbakhsh, 2005; Pinna & Grossberg, 2005). While the FAÇADE model is still a valid account of the complex interactions between the these systems (Grossberg, 2016), the LAMINART model seeks to pinpoint more intricate or specific sub-operations within these systems including those that relate to three-dimensionality (Grossberg, 2003b). Grossberg himself describes the model as a laminar cortical realization and extension of the original FAÇADE model. Based on the LAMINART model, WCI stimuli processing would be more limited to cortical layers 4 and 6 of V1 and V2. Despite differences between FAÇADE and LAMINART in regard to the exact location of the mechanisms responsible for color spreading illusions, both models argue it occurs cortically and largely along the ventral stream within the striate and extrastriate cortex.

The purpose of discussing color spreading illusions rather interchangeably relates to research suggesting similar or identical mechanisms are responsible for this class of illusion. Pinna and Grossberg (2005) discuss a unified explanation for NCS and the WCI, noting that they are "two classes of phenomena that enable visible colors of the surface stream to be dissociated from figural properties that are initiated in the boundary stream" (p. 2208). Both of these color spreading effects fit the FAÇADE model as they each have feature, boundary, and depth components. Pinna and Grossberg (2005) sought to create what they refer to as a "limiting case" that would provide evidence for a unified neural model of these illusions (see Pinna & Grossberg, 2005, Fig. 10). By modifying specific NCS stimulus parameters, stimuli can be created that are in between NCS and the WCI. This suggests that the primary differences noted between color spreading illusions (e.g., transparent film vs opaque surface, radiant light vs pale light) may simply be due to the basic stimulus parameters intrinsic to each illusion. For instance, the translucent appearance of a traditional NCS surface may appear this way only due to the continuous nature of the contours that appear to run beneath the surface. In contrast a WCI surface is more likely to appear opaque since no such contours exist to suggest transparency. In this case the strong figurality associated with color spreading illusions creates a perception of a depthful solid surface rather than the translucent film created in NCS stimuli. The color surface of a WCI stimulus can even be made to appear transparent if a non-uniform background is used (see Figure 3). In all of these cases however, the "feature" (i.e., color spreading) and "boundary" (i.e., figurality) components of the stimulus interact to generate a perception of a color surface occluding (or simply positioned above in depth) the surface below. These similarities indicate a common set of neural processes for color spreading illusions with differences arising only when specific stimulus elements are present thus generating one color spreading illusion rather than another.

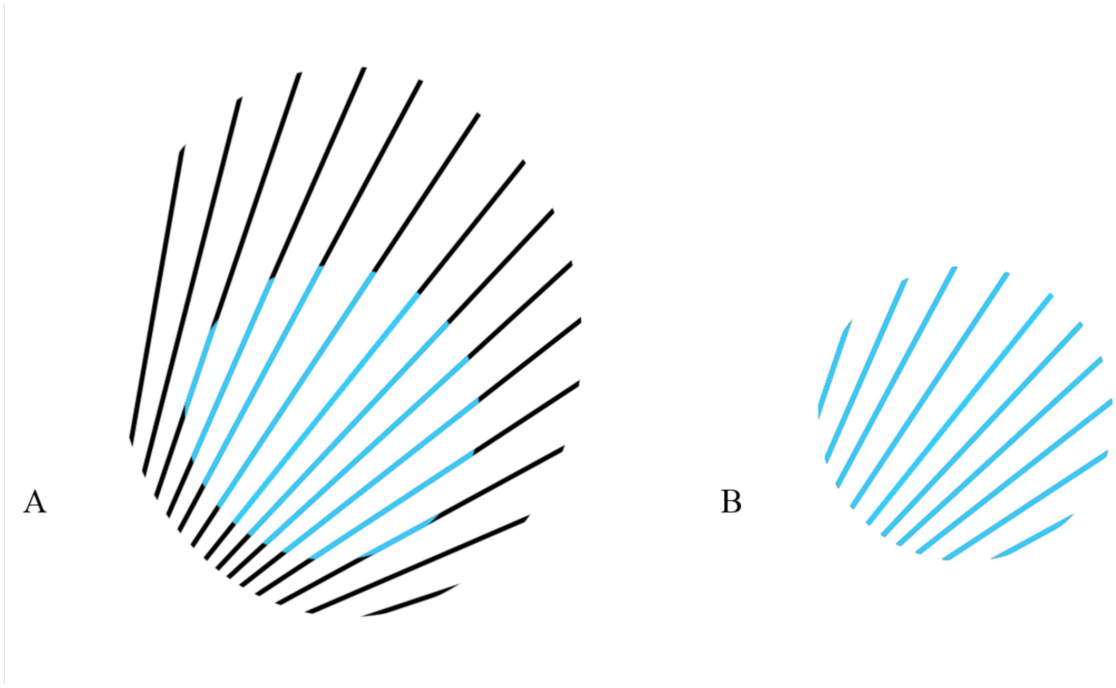


Figure 1. (A) - An example of neon color spreading consisting of an pattern of black contours with a subpattern of superimposed blue contours; (B) - The identical subpattern in (A) with the surrounding portion of the stimulus removed.

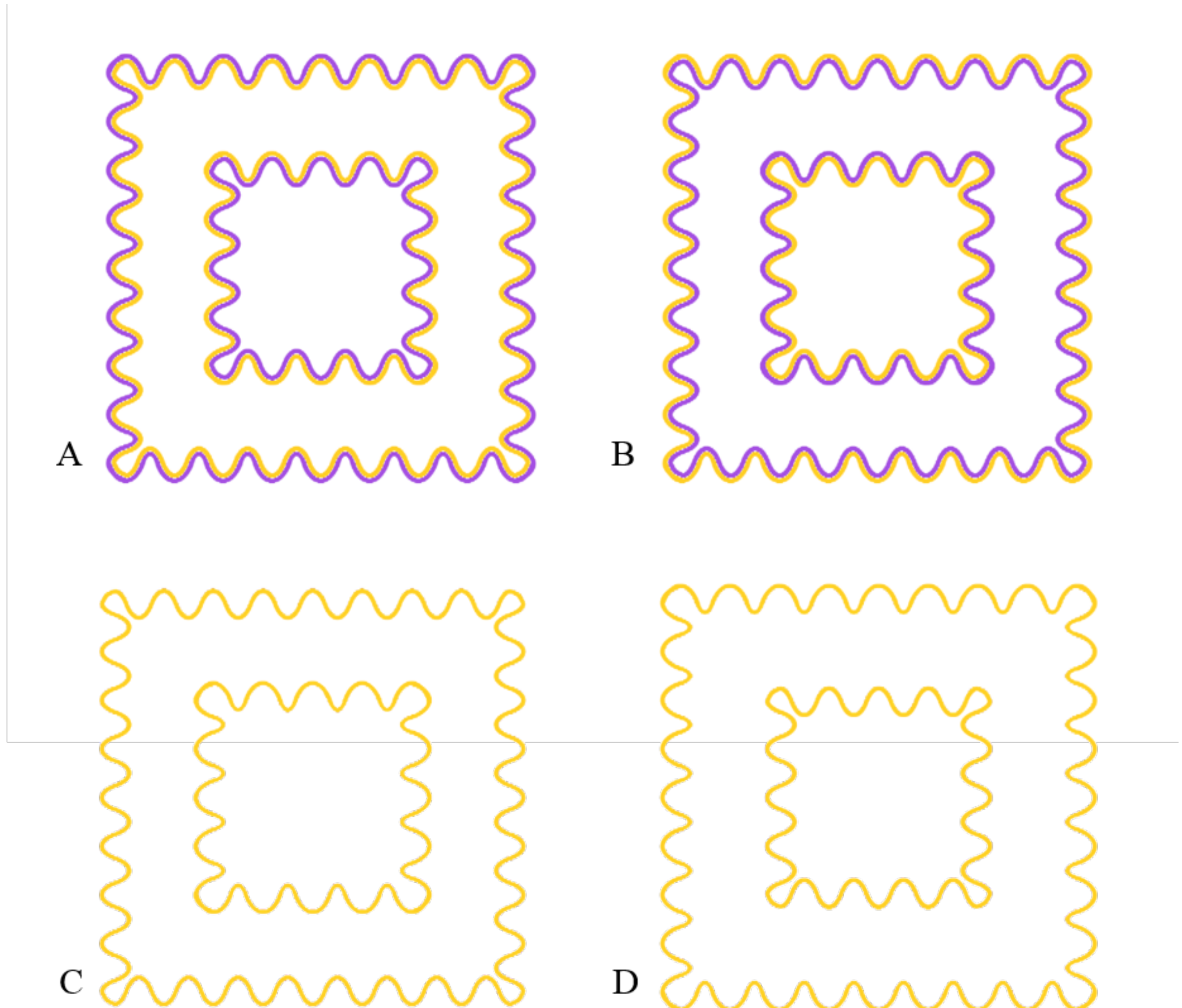


Figure 2. Two examples of the watercolor illusion. The placement of the purple outer contour and orange inner fringe in (A) results in a light orange square figure with an apparent white hole in the middle. Conversely (B) appears to be a light orange square figure floating in front of a white larger square. Note that the color spreading from the outermost fringe on (B) extends weakly across this entire page. This can be confirmed by comparing this page to the perceived whiteness of the larger white square on the right or the smaller white square on the left. The purple border from (A) and (B) were removed from (C) and (D) respectively to demonstrate that the fringe alone is not sufficient to generate this illusion.

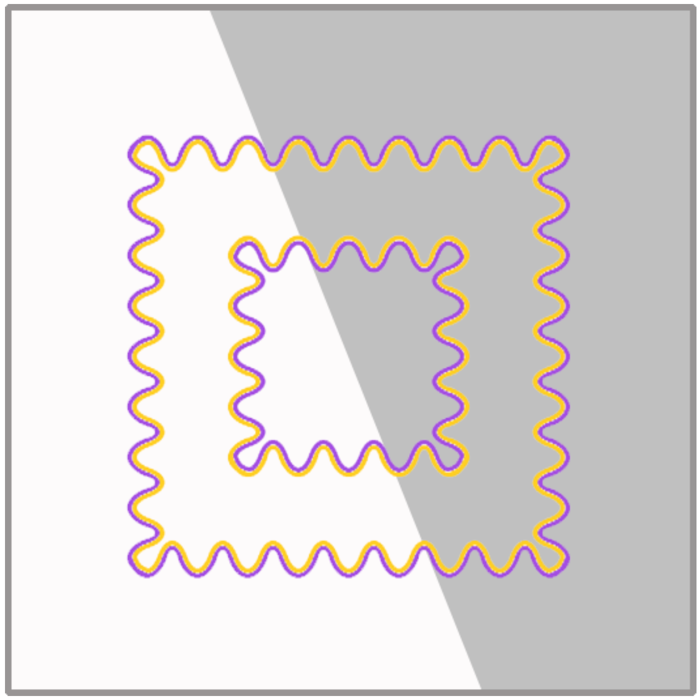


Figure 3. Example of a WCI stimulus with a discontinuous background resulting in a reduction in illusion magnitude now that the perception of surface solidity is lost.

CHAPTER 2

COLOR SPREADING IN CONTEXT

Visual illusions provide researchers with a unique opportunity to shed light on the limitations and ultimately the functionality of the human visual system. Since many color spreading illusions seem to share similar mechanisms and perceptual qualities, it follows that studying one of these illusions to discover more about visual system limitations or functionality would have implications for any other from this class of illusions. Therefore we shall focus only on the WCI with the implied understanding that these discussions and findings may and likely do relate to an entire class of color spreading illusions.

Research in this field to date has largely focused on (a) how specific stimulus parameters affect WCI magnitude and (b) what mechanisms likely generate the illusion. Rarely however, has research into these illusions addressed if our normal visual experience is influenced by illusory color spreading. Pinna & Grossberg (2005) discuss how a WCI surface can generate a perception of three-dimensionality by appearing to be raised or physically above the background. Pinna and Reeves (2006) note that this figurality imparted by the WCI can become an advantage or disadvantage depending on semantic expectation. For example, the stimuli used in their study were aerial-perspective drawings of well-known land masses abutting bodies of water (e.g., the southeastern United States abutting the Gulf of Mexico and the Atlantic Ocean). As land inherently rises higher into space than water, the placement of a WCI surface on the land or in the water can become an advantage or a disadvantage respectively in terms of recognition speed for the "scene". It is important to note that the term "scene" used here refers to the map-like stimuli used in this experiment. However, this is dissimilar from how the term will be used hereafter due to the specific nature of the top-down information provided in Pinna and Reeves' stimuli – namely that these stimuli would only be able to be perceived naturally from an extremely high and therefore unlikely vantage point (e.g., viewed from space). Instead, it is presumable that individuals capable of identifying these stimuli are recalling some combination of pictures from space and/or maps that represent this "scene" from its natural vantage point. While one could argue that a picture or a map may represent a scene, the actual distal stimuli (i.e., land and water masses) being represented in these WCI line drawings are simply too large and from too unlikely a vantage point to be considered scenes humans would normally view. If we are to examine the way in which color spreading illusions interact with our normal visual experiences, the stimuli used must be more representative of the environment in which we normally perceive and interact.

While these studies begin to address color spreading from a more three-dimensional perspective, they fall short of addressing how this may relate to perceiving our actual three-dimensional environment. Additionally, there is an important middle ground to be explored between studying this phenomenon from the lowest (e.g., parameters of abstract stimuli) and highest (e.g., object/scene recognition) levels. This exploration could begin with how basic color spreading illusion stimuli react to the addition or subtraction of local features. For example, previous research has demonstrated that an unenclosed WCI stimulus will spread color beyond the borders of the stimulus itself until it reaches another border – even if that border is the edge of the page or screen on which the stimulus is being viewed (Pinna, 2005; Pinna et al., 2001; see Figure 4A & 4B). This configuration is not optimal in terms of stimulus strength for the WCI. This results in a weakened color across the entire spreading region – not just the area outside of the stimulus borders. The uniformity of this illusory degradation demonstrates how local stimulus changes (i.e., an unenclosed region) can affect global processing.

One could argue that the global processing of unenclosed WCI stimuli such as these and the surrounding area is quite similar to normal visual processing of a real-world scene. Imagine for a moment that the serpentine border and fringe from Figure 4A were actually a length of rope light[1] laying in the same serpentine configuration on a white floor. This rope light was designed to only emit orange light from one side. In this hypothetical example, the orange would appear strongest along the rope itself since this is the source emitting the orange light, and the strength of the orange light would dissipate in a subtle gradation dependent on a set of factors including the strength of the light source itself, obstacles the light may encounter, the reflectiveness of the floor, ambient room lighting, etc. Now imagine that this serpentine rope was a tube instead that was releasing a hazy orange gas (like a fog machine) from one side rather than the light being emitted in the previous example. Assuming the room was equally illuminated from above and the gas was not able to cross the gas emitting tube barrier, the orange gas would be visible spreading evenly across the white floor and dissipating gradually into the open space beyond the barrier of the tube. Both of these examples are somewhat contrived, but they are meaningful in understanding how the visual system organizes and "makes sense" of the scene as a whole. Pinna and colleagues (2001) discuss unenclosed WCI stimuli only from a bottom-up (i.e., "feedforward") perspective. However visual stimuli are also processed in a "feedback" direction allowing for top-down information to influence low level processing (Kafaligonul, Breitmeyer, & Ögmen, 2015; Lamme, Super, & Spekreijse, 1998). This bidirectional processing of visual stimuli suggests our visual system is likely to prefer an interpretation of a given stimulus that is consistent with our visual experiences – even in abstract stimuli lacking semantic information.

[1] Rope lights are a flexible strand of lights encased in a plastic tube. In this example, the plastic tube is clear on one side and completely opaque on the other.

Individuals describe the color that spreads across a NCS stimulus as being “hazy” or “foggy” whereas the color in an enclosed WCI stimulus tends to be described as “solid” or “dense”. These descriptors are important because they suggest an impression of depth as well as a connection between these illusory experiences and other (i.e., remembered or imagined) real-world visual experiences such as the rope light and gas hose examples. It does not matter whether or not anyone sees the image in Figure 4A as a rope light or a gas hose to the level of specificity provided here; the processing is likely to be the same based on the combination of feedforward processing of low level features and feedback processing of complex visual stimuli such as scenes and objects previously experienced.

Thinking about color spreading illusions as being processed in this bidirectional global context also supports the idea the specific configuration of the stimulus at both local and global levels is the sole difference between types of color spreading illusions (e.g., NCS, the WCI). For instance, the color spreading seen in Figure 3 appears transparent and foggy which is more indicative of the appearance of color spreading in typical NCS stimuli than in WCI stimuli. This is due to the change in background luminance behind the stimulus. Since this background luminance change is visible outside and inside the WCI stimulus border, two interpretations are possible. The first option is the surface of the stimulus is a transparent colored “film” through which the background is visible despite being discolored somewhat due to the specific hue of the film through which it is being viewed. The second option is the surface of the WCI stimulus is an opaque solid surface floating above the background which is identical to the background in terms of orientation, general luminance, and position with a subtle change in hue across the entire surface. The first option is much more likely than the second option based on logic and on our past visual experiences so it is also likely to be the interpretation chosen by our visual system (i.e., that we perceive). If the entire background were a single luminance (including within the WCI surface), the perception of the WCI surface would return to that of an opaque solid. If the background were white, this perception as well as the strength of the illusion would be strengthened even further. Finally, if the WCI surface was a single luminance different from the two luminances making up the background, there would be no reason to see the surface as transparent. This global configuration would strengthen the perception of an opaque solid surface since the WCI surface differs from what is likely behind or underneath the surface (i.e., the background) based on the Gestalt principle of good continuation.

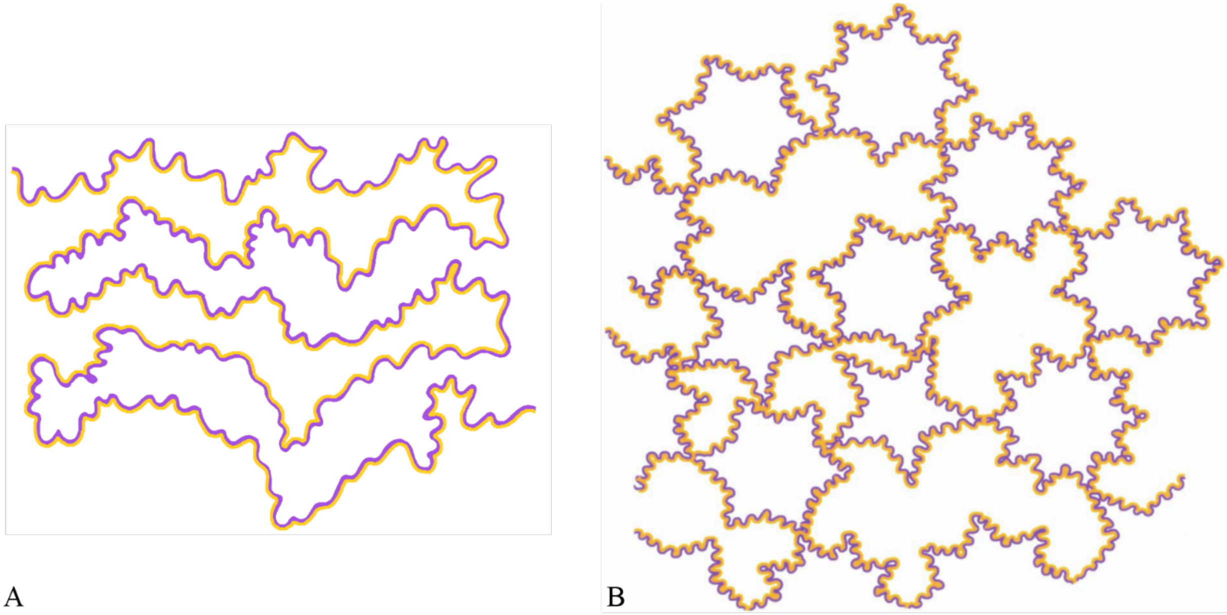
The WCI stimulus in Figure 3 and the hypothetical variations described above highlight the impact of global configuration on illusion appearance. NCS appears to be transparent because the global appearance of a transparent colored film across a portion of a pattern of contours is the most logical and likely explanation based past visual experiences. This explanation is identical to the transparent appearance of color spreading in Figure 3 despite this being a WCI stimulus. Differences between these illusions exist due to the local and global configurations and how these configurations affect bottom-up and top-down processing. A typical NCS stimulus is unenclosed in terms of the color spreading region. Rather than the color slowly dissipating as it does in unenclosed WCI stimuli (see Figure 4), the illusory color abruptly stops resulting in an illusory colored contour surrounding the color spreading region (see Figure 1A). This interpretation may even reinforce the low-level factors that are causing the reduction in the illusion thus suppressing the illusion not only in the areas outside the borders but those inside the borders (i.e., closest to the inducing orange fringe) as well. This creates a visual experience that is consistent with top-down information from any hypothetical scenario. It is not necessary to imagine one of the scenarios described here to still have a visual experience impacted by a combination of feedforward and feedback processing (Kafaligonul et al., 2015). Our visual expertise with the world around us remains a driving factor even in the perception of new visual experiences.

The illusory "filling-in" of color experienced in color spreading illusions is similar to many of the models and explanations of surface completion in real-world viewing scenarios (Sharf, Alexa, & Cohen-Or, 2004; Yin & Kellman, 1997). For example, the point at which the optic nerve leaves the eye causes a blind spot due to the complete absence of receptors there. This region in each eye is perceptually filled-in however using visual stimulation such as brightness, color, and texture from surrounding receptive fields resulting in a completed visual perception (Pessoa & De Weerd, 2003). Similar processes are implemented by the visual system to fill-in brightness (Rossi & Paradiso, 2003), texture (Park, Guo, Shin, & Qin, 2006; Spillmann & De Weerd, 2003), and – most importantly for this discussion – color (Von der Heydt, Friedman, & Zhou, 2003) in occluded (i.e., amodal completion) and non-occluded (i.e., modal completion) surfaces (Davis & Driver, 2003; Grossberg, 2003a; Mendola, 2003) that do not lie in a blind spot or scotoma region. Color filling-in can also occur as a result of neural adaptation as with Troxler fading (Bonneh, Donner, Cooperman, Heeger, & Sage, 2014).

In order to perceive color in a particular region, color information must be obtained by the visual system either within that region or in an area surrounding that region. Figure 5 depicts three different ways in which this could occur as described by von der Heydt (2003): the naïve concept, the color filling-in theory, and the symbolic color representation theory. The physical stimulus and subsequent perception of this information is identical in all three cases (i.e., an orange circle on a gray surface). Based on the naïve concept as described by von der Heydt (Figure 5A), receptive fields (RFs) falling on random positions across the entire stimulus will respond to wavelength information resulting in the perception of an orange circle. This theory places little emphasis on any global role within this visual field. For the orange to be perceived there must actually be wavelength stimulation for RFs located in the center of the orange circle. In this model, individual RFs are not well integrated. Therefore RFs at the circle's border will not contribute very strongly to color perception due to the interaction of inhibition and excitation within each RF. The color filling-in theory (Figure 5B) allows for lateral processing between RFs at the circle's border. These signals are kept strong due to the combination of horizontal connections and strong color contrast between the orange circle and surrounding gray surface. The dotted contours in this figure connecting the orange surface to the processing taking place at the border of the circle represent the weaker and more unreliable afferent signals from any individual RFs within the orange circle. The symbolic color representation theory (Figure 5C) is similar to the color filling-in theory in that RFs at the border (rather than random RFs at the center of the orange circle) are most important for perception of the orange circle. In this theory however, the form of the circle is also processed. Border-selective RFs integrate at a higher level to generate a neural signal that signifies the presence of an orange circle. Here, it is the global configuration of the visual field that is ultimately generating the perception.

All of these theories are discussing visual processing of wavelength information in stimuli under normal viewing conditions. Nevertheless, scotomas as well as filling-in from adaptation (e.g., Troxler fading) could also be explained using either the color filling-in theory or the symbolic color representation theory. In fact, it would be in the interest of our visual system to implement a process like the ones proposed in these theories for all surface color processing due to the benefits of increased processing speed and better integration of information across the visual field. Thus, in addition to attempting to explain the perception of color under normal conditions, these theories of filling-in can also be used when trying to explain the different types of illusory color observed in color spreading illusions. While it is possible illusory color spreading is simply a byproduct of normal physiological processing of retinal stimulation, it is likely these illusions are visual evidence of a ubiquitous color filling-in process that is constantly functioning and interacting within the global context of our visual experience.

We know with an unenclosed WCI stimulus the perception of color will spread relatively far beyond its border (see Figure 4). However, a real surface does not “leak” its color into space – regardless of the filling-in mechanism implemented by the visual system to perceive the surface’s color. For example, within the FAÇADE/LAMINART models this is due to the BCS which is responsible for creating “end-cuts” at the ends of lines/boundaries that stop color from leaking (Grossberg, 2014). Theoretically, if these end-cuts were not created color would leak into space even in real-world viewing conditions. The following experiments examine how various global contextual factors can interact with color spreading and filling-in for a variety of enclosed and unenclosed WCI stimuli. We will investigate how these color spreading and filling-in processes behave under these new contexts.



A B

Figure 4. Examples of unenclosed WCI stimuli. (A) - In a serpentine design similar to a stimulus found in Pinna et al. (2001) color tends to spread away from an unenclosed WCI stimulus. (B) - A mix of enclosed and unenclosed regions similar to a stimulus found in Pinna & Grossberg (2005) demonstrate that the stark white area inside the central “stars” is notably different than the surrounding area despite both areas being the same physical white. It is the unenclosed WCI regions “leaking” color into the surrounding area that creates this apparent difference.

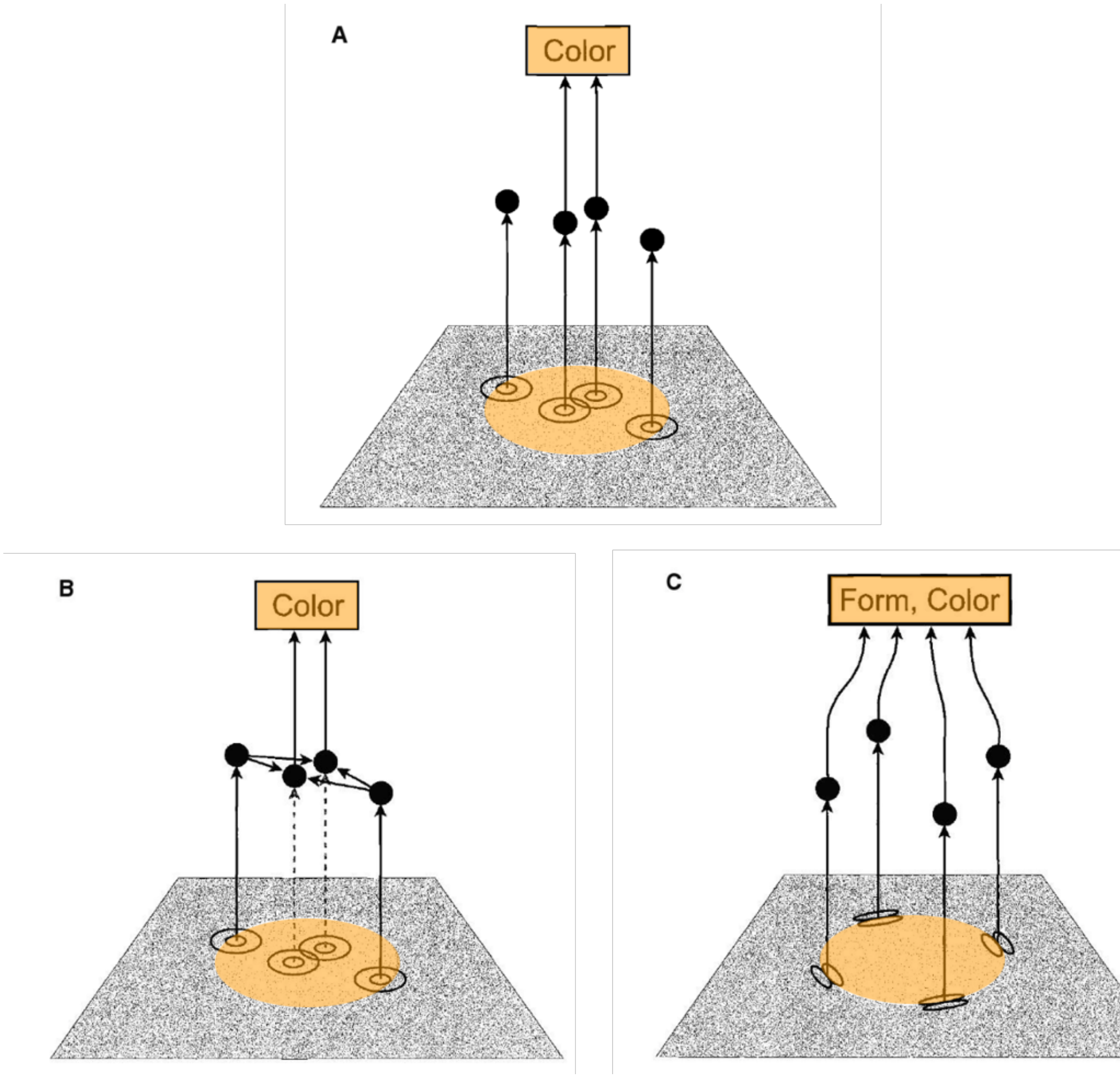


Figure 5. Adapted from von der Heydt et al. (2003) depicting three different theories of surface color neural representations for an identical colored region: (A) the naïve concept, (B) the color filling-in theory, and (C) the symbolic color representation theory.

CHAPTER 3

EXPERIMENT 1

The ability to recognize color in the natural world evolved independently on several occasions in the animal kingdom (Pinna & Reeves, 2015). Therefore it is logical to assume that color plays a vital role in processing stimuli of interest in the environment for a variety of species. Research examining color spreading illusions has traditionally used drawings or pictures of abstract shapes and contours to generate a specific perception. While these types of stimuli can elicit a high illusion magnitude for the observer, they are not very representative of the types of stimuli we see in our normal daily visual experience. For example, some research suggests that color spreading illusions such as the WCI and NCS may hint at the purpose of color for humans in general including helping to unify surfaces and objects, enhancing amodal completion, and fragmenting visual stimuli into separate parts (Pinna, 2011; Pinna & Reeves, 2015). Providing one of the few examples in "natural conditions", Pinna and Reeves (2015) show an image of a flower exhibiting a faint NCS effect. One could argue that the vibrant colors often found on flowers such as these serve a similar purpose for insects and other organisms as it does with humans. Perceiving more color than is actually present would be beneficial for pollinators and for the plants being pollenated.

To further investigate color spreading in conditions more closely resembling the real world, a range of stimuli were created spanning from pictures of two-dimensional shapes to a variety of pictures of "objects" more representative of the three-dimensional world. This approach should provide useful information regarding the perception of color spreading as stimuli progress toward depictions increasingly more similar to the three-dimensional world allowing us greater insight into the role color spreading may have in visual perception. Additionally, since stimuli of this nature have never been tested under these conditions, our results should provide additional data for the FAÇADE and LAMINART theories to consider in terms of boundary, feature, and depth systems including three-dimensionality.

For the first condition of Experiment 1, three simple shapes (i.e., a square, pentagon, and hexagon) were drawn with the typical WCI fringe and contours (see Figure 7). This condition served as a baseline for the other conditions in this experiment. Given the shapes to be tested we chose to use straight contours which, while not optimal for maximizing the perceived color, still produce color spreading (e.g., Pinna et al., 2001). The baseline condition should have the highest magnitude estimation ratings in this experiment based on the configuration and features of these stimuli compared to the other conditions (see Pinna et al., 2001). This condition also served as a comparison baseline between Experiment 1 and 2[2].

Condition 2 served as a baseline for the pictures of three-dimensional configurations used in Condition 4. The same shapes from Condition 1 had an additional region added resulting in a two part shape with no fringe in this new region/part (see Figure 8). This allowed us to determine how the WCI manifests in this configuration alone before examining the full three-dimensional configuration to determine what parts of the stimulus are driving any measurable differences in illusion magnitude and/or spreading. The literature to date suggests color spreading will continue well beyond a WCI region that is unenclosed (i.e., no border exists to stop the spreading); however the saturation of this perceived color degrades uniformly the larger the spreading area becomes (Devinck et al., 2005; Pinna, 2011; Pinna et al., 2001; Pinna & Grossberg, 2005; Pinna & Reeves, 2006, 2015). Pinna and colleagues (2001) found color spreading dissipated

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[2] See Table 2 for a complete breakdown of conditions, stimuli, and planned comparisons for Experiments 1 and 2. This table should visually aid the explanations and discussions of these conditions.

substantially across a space greater than 45º of visual angle; however spreading in that experiment took place in an enclosed region. See Figure 2B for an example of this phenomenon in an unenclosed configuration. In this figure the outer contour and fringe from Figure 2A have been reversed resulting in a small orange square seemingly floating above a larger white region. Outside of this white region, an orange tint spreads in all directions until it reaches another border – the edges of the page on which it is printed. To confirm that this perception exists, the page can be compared to the small white "hole" in 2A or to the larger white region in 2B. While physically identical, they are clearly perceptually different.

Based on current literature, the color spreading in Condition 2 should extend into the new region (i.e., from "Region 1" into "Region 2"; see Figure 8) since no physical border exists between these regions. However since this new region is less optimal for color spreading than Condition 1 (i.e., no fringe inside the Region 2) we should expect a slight reduction in illusion magnitude similar to the aforementioned studies and example. However if color spreading fails to enter this new region, this would suggest an additional mechanism is interfering in the ability of this color to spread as expected. This would shift this condition from a baseline condition to an experimental condition evaluating the nature of color spreading within each part of the shape. It is important to mention that this condition was tested prior to the three-dimensional conditions so participants' perceptions would not be biased towards a more three-dimensional organization of the stimuli. Nevertheless, because it was possible the shapes in Condition 2 could potentially be viewed as somewhat three-dimensional, potentially impacting the likelihood of color spreading into the non-fringe region, a pilot study was conducted to assess their perceived three-dimensionality (see Table 1). Using a Likert-type scale from 1 – 7 where "1" was two-dimensional/flat and "7" was three-dimensional/depthful, the average ratings for all stimuli in this condition was a 1.71. This suggests participants did not see the pictures of these stimuli as particularly depthful – especially when compared to the pictures of their three-dimensional counterparts in Condition 4 which had an average depthfulness rating of 6.86 out of 7. Therefore, any differences found between Condition 2 and Condition 4 would only subtly be influenced by depth.

Another possible factor that could influence the perception of Condition 2 had to be considered. If participants perceived the non-fringe region to have zero color spreading while simultaneously perceiving the fringed region as filled-in with color, then they were automatically perceptually organizing this single shape into two distinct parts. This would seem to support viewpoint invariant models of object recognition which suggest a single representation is activated whenever a shape or object is observed despite the relative viewpoint of the observer (Marr & Nishihara, 1978). The Recognition-By-Components model posits that object recognition occurs due to the relative configuration of objects parts (termed "geons" in the model) analogous to the perception of speech blooming from a finite number of more basic phonemes (Biederman, 1987, 2001). We might infer observers who perceive the stimuli in Condition 2 this way may even perceive an illusory color contour similar to that of NCS belonging to the color spreading surface and defining the separation between the regions. To our knowledge an illusory color contour has never been reported with the WCI. This would provide further evidence for color spreading illusions sharing common neural mechanisms with the only differentiating factors between specific illusions being local and global stimulus configural factors (Pinna & Grossberg, 2005). Interestingly, one could argue an automatic perceptual dissection of a surface caused by an illusory color contour may be revealing an existing object recognition process. If the fringe was removed from inside the shape then an illusory contour would not exist – colored or otherwise. It is the perceived color within one region and not the other making this segregation visible; it is not necessarily the cause of the initial segregation. The color spreading stops when it reaches a border. This border – whether physical, illusory, or an unconscious implication due to configuration – logically must exist prior to the full perception of color spreading. This is not to say the mechanisms responsible for color spreading could not be operating at near simultaneity. Rather this implies the process of neurally constructing these stimuli would likely start with encoding the more basic stimulus parts making up each regardless of the existence of the fringe or color spreading. An illusory color contour would simply make this process visible. If this were true for one stimulus in this condition it would be true in the other two. Additionally it would be true if you were to rotate these images to any other angle. This would be more difficult to reconcile using view-specific models such as those argued for by Riesenhuber and Poggio (2002), Buelthoff and Edelman (1992), Tarr and Pinker (1989), and others.

If participants perceive color spreading throughout the entire shape as originally hypothesized rather than as two parts divided by an illusory color contour we will be able to see how configurations more representative of our three-dimensional world impact this phenomenon. For instance, we will be able to test whether perceived three-dimensionality is sufficient as a configural cue in eliciting a stronger illusory color contour compared to a two-dimensional baseline.

Condition 3 consisted of pictures of three-dimensional versions of the original shapes from Condition 1 resulting in a cube, a pentagonal prism, and a hexagonal prism. The fringe was only present within the original shape surface, not in any of the new object surfaces (see Figure 9). This is the first study to examine the WCI within the context of three-dimensional object representations. To study the WCI under more ecologically valid conditions of we must begin to examine how the WCI manifests in configurations more closely resembling real-world surfaces and objects. While a picture of a three-dimensional shape on a white background is not the same as a true visual scene (e.g., not a physical object existing in space, no meaningful background, no illumination cues) it does methodically begin move the research in a more ecological direction. This condition served as a three-dimensional control for Condition 4. Since the WCI surface is fully enclosed as in Condition 1, the illusion magnitude is expected to be similar to Condition 1.

Condition 4 began to probe how the WCI "reacts" when certain components of the three-dimensional configuration are removed. The same pictures of three-dimensional objects used in the Condition 3 were used here except one side of the color spreading front surface was removed including both the outer contour and the fringe (see Figure 10). As with Condition 2, previous literature would suggest the WCI should spread into this additional space in the absence of a physical border. We predicted the global configuration of these stimuli should be sufficient to stop the color spreading from "going around the corner" into the adjoining region. This would suggest the visual system is still treating this "unenclosed" region as a separate surface due to its implied orientation within the object. A faint illusory color contour may be perceived separating this single two-dimensional region into two parts: a solid orange surface on one side and a solid white surface on the other. Despite the nature of color spreading expected, the illusion magnitude was expected to be lower in this condition than in Condition 3 for a couple reasons. First, removing one side decreases the amount of fringe available to induce the illusion. Second, even if an illusory color contour is perceived it is likely to be a less optimal border than the physical boarder in Condition 3. This was previously discussed in a similar way in regards to comparing Conditions 1 and 2. To determine how the addition of three-dimensional global shape information impacts the WCI we compared Condition 4 to the baseline stimuli in Condition 2.

Since the WCI has never been studied using three-dimensional configurations like this, the design of these four conditions was titrated in such a way as to probe the effect of stimulus configurations for color spreading stimuli that are increasingly more representative of our three-dimensional world.

General Method

Participants. A total sample of 45 undergraduate student participants from the University of Georgia research participant (RP) pool was selected (i.e., 15 per experiment). All participants had normal or corrected-to-normal vision as verified by acuity and phoria testing, normal color vision as verified by pseudoisochromatic plates, and no history of an attention deficit disorder. Participants were at least 18 years old at the time of the experiment. All research was conducted in accordance with the Declaration of Helsinki and under the approval of University of Georgia Institutional Review Board (IRB) ethical guidelines for research involving human participants. All participants received partial course credit as compensation for their participation.

Stimuli and Apparatus. Images were presented on a cathode ray tube (CRT) monitor operating at an 85 Hz refresh rate using E-Prime v3 software. Participants viewed the monitor from 172.4 cm creating a visual angle of 8.6° (height) × 12.1° (width) in a room with low illumination from an 11w "natural daylight" bulb[3]. Responses were recorded using the computer keyboard. A chin and forehead rest was used to minimize head movements and fix gaze distance. Images were created using Adobe Photoshop. The border of the all WCI regions was divided into a contrasting outer contour and inner "fringe" subtending 6' of visual angle. These contours were straight for Experiments 1 and 2 and wavy for Experiment 3. Similarly to Pinna and colleagues (2001) and Pinna and Reeves (2005), the outer contour was dark purple (RGB: 165, 80, 226;

[3] Low illumination was necessary for participants to see the handwritten measure cards.

25.02 cd/m^2) and the inner contour was light orange (RGB: 255, 207, 37; 54.09 cd/m^2) to optimize a strong color illusion. All stimuli consisted of a central object or objects on a white (RGB: 255, 255, 255; 59.08 cd/m^2) background. A comparison stimulus was used during instructions and prior to each trial (see Figure 6). The comparison stimulus for Experiments 1 and 2 consisted of two purple abutting squares located in the center of the screen with fringe inside the square on the right and no fringe inside the square on the left. The numbers "1" and "7" were written under each square, respectively. For Experiment 3, the enclosed WCI stimulus from Condition 1 (See Figure 21A) was used as the comparison stimulus for Condition 1 and 2, and the enclosed WCI stimulus from Condition 3 (See Figure 23A) was used as the comparison stimulus for Condition 3. The numbers "1" and "7" were visible in a region of zero spreading and maximum spreading, respectively.

Design and Procedure. For all experiments participants adapted to the low room lighting for five minutes before beginning the experiment. In this time, the experimenter explained the procedure and asked if the participant had any questions. Participants gave magnitude estimations in Experiments 1 – 3 with a Likert-type scale from 1 to 7 where a response of "1" indicated no color spreading is present, "4" indicated a moderate illusion magnitude, and "7" indicated maximum illusion magnitude. A comparison stimulus was shown prior to each trial allowing participants to see an example of a "1" and a "7" on this scale before making each response. See Figure 6 for an example of a trial breakdown. Ratings were made using a computer number pad and the "enter" key to record their response. For conditions with only one rating, pressing "enter" automatically started the next trial. For conditions with two ratings (e.g., Experiment 1, Condition 4), participants pressed "enter" to submit their first rating and then pressed "enter" again to submit their second rating and advance to the next trial. All responses were also visible on the screen (i.e., the first response displayed in red, the second response (if any) displayed in purple).

Participants completed three trials for each stimulus type. The first trial of any stimulus type per condition was treated as a practice trial and removed prior to analyses. Therefore there were 24 experimental trials in Experiment 1 (i.e., 36 total minus 12 practice), 42 experimental trials in Experiment 2 (i.e., 63 total minus 21 practice), and 24 experimental trails in Experiment 3 (i.e., 36 total minus 12 practice). Participants were also asked to complete a handwritten measure for each stimulus type in Experiments 1 – 3 at the end of each condition (see Appendix A.1 – A.3). On a printed black outline version of the onscreen stimulus (i.e., one of the stimulus types for that condition), participants used a pencil to shade in the region in which color spreading was perceived. These printed stimulus cards were handed to the participant one at a time and collected after the completion of each card.

For Experiment 1 all participants completed Condition 1 first, and the order for the following three conditions was counterbalanced. For Experiment 2 all participants completed Conditions 1 and 2 first, and the order for the following five conditions was counterbalanced. For Experiment 3 the order for all three conditions were counterbalanced. Trials were randomized between stimulus types within each condition (e.g., between square, pentagon, and hexagon in Condition 1). The handwritten measures were also counterbalanced within each condition. Since participants complete the handwritten measures by shading what they see on the screen (i.e., the same images from the rating task displayed once again), the order in which these images were displayed were in a counterbalanced order between participants. Once all conditions have been completed for any given experiment, the experimenter debriefed the participants.

Analyses. Homogeneity of variance was confirmed for all participant groups as Levene's test of equality of error variances was not violated for any statistical test in Experiments 1 – 3, $p < .005$. All pairwise comparisons were collapsed across Shape in Experiments 1 and 2 and across Condition in Experiment 3. The handwritten shading data from Experiments 1 – 3 was coded to determine the percentage of participants who perceived color spreading across the stimulus. See Figures 12, 20, and 25 for this data displayed in "heat maps" for Experiments 1 – 3, respectively. Heat maps were created using a conditional formatting grid in Microsoft Excel. Additionally, the "Notes" sections (see Appendix A1.1 – A1.3) for the handwritten measures did not produce any meaningful qualitative data that was not already recorded via the magnitude ratings and/or the shading data.

Experiment 1 Method

Stimuli. Four sets of three stimuli were created for Conditions 1 – 4 respectively resulting in a total of 12 stimuli for Experiment 1. Stimuli for Condition 1 consisted of pictures of one of three possible centrally located two-dimensional shapes (i.e., square, pentagon, and hexagon). The square, pentagon, and hexagon all fit within a region subtending 2.40° of visual angle. Condition 2 stimuli consisted of shapes similar to Condition 1; however one border from Condition 1 was removed and an additional set of borders existed devoid of fringe. These shapes all fit within a region subtending 2.80° of visual angle. Condition 3 consisted of pictures of three-dimensional figures that incorporated Condition 1 with fringe only in the foremost surface (i.e., cube, pentagonal prism, and hexagonal prism). These central objects now all fit within a region subtending 2.80° of visual angle to accommodate their three-dimensional size. Stimuli for Condition 4 were identical to Condition 3 except one side (including the outer contour and inner fringe) of the surface containing the WCI fringe was removed (similar to Condition 2).

Design and Procedure. For all conditions participants reported the illusion magnitude of the interior of the two-dimensional shape or foremost surface of the three-dimensional shape (i.e., Region 1). Condition 2 and 4 required participants to also report the illusion magnitude and extent in the additional region (i.e., Region 2). Brief instructions were provided prior to each condition to ensure the participants understood to which region or regions they were responding. Participants completed the handwritten measures as detailed in the General Methods.

Experiment 1 Results and Discussion

A 4 (Condition) x 3 (Shape) within-subjects ANOVA was conducted to analyze the hypotheses laid out in Experiment 1 using the Region 1 magnitude estimation data only. The purpose of having three different shapes was to ensure that our findings were not due to the specific configuration of any one of them. Therefore we did not expect to find a main effect of Shape; however a main effect of Condition should be found due to the anticipated weakening of the WCI in the spreading region once a border had been removed (i.e., Condition 4 and potentially Condition 2). As predicted, there was a significant main effect of Condition, $F(3,168) = 3.961$, $p = .009$, no main effect of Shape, $F(2,168) = .517$, $p = .597$, and no significant interaction, $F(6,168) = .146$, $p = .990$ (see Figure 11). As noted in Table 2, there were additional planned pairwise comparisons between conditions. The first hypothesis that Condition 1 would not be significantly different from Condition 3 was disconfirmed since Condition 3 ratings were significantly lower than ratings for Condition 1, $p = .004$. As predicted, Conditions 2, $p = .011$, and 4, $p = .004$, ratings were statistically lower than Condition 1 due to the missing border in these two conditions. Just as Condition 1 was the baseline for Condition 3 to determine what impact three-dimensionality had on illusion magnitude, Condition 2 was the baseline for Condition 4. Condition 2 was not significantly different from Condition 4, $p = .712$, indicating these stimulus changes (e.g., perceived three-dimensionality, removal of a border) are sufficient to reduce illusion magnitude. This could explain why Conditions 1 and 3 were different but Conditions 2 and 4 were not. The last planned pairwise comparison hypothesized that Condition 4 would have statistically lower magnitude ratings than Condition 3. These conditions were identical except for the removal of the border; however this physical difference between conditions did not generate any significant difference in illusion magnitude between the two conditions, $p = .977$.

The relative difference in illusion magnitude between Region 1 and Region 2 in Conditions 2 and 4 is also informative in regard to how this illusion manifests in stimulus configurations more representative of the three-dimensional world. Therefore, a 2 (Condition) x 3 (Shape) x 2 (Region) within-subjects ANOVA was conducted. A main effect of Condition was predicted but did not exist, $F(1,168) = .088$, $p = .768$, suggesting participants had a similar visual experience for two-dimensional (i.e., Condition 2) and three-dimensional (i.e., Condition 4) representations of the combined area inside Regions 1 and 2. This is confirmed by the statistically significant main effect of Region, $F(1,168) = 228.997$, $p < .001$. There was not a significant main effect of Shape, and there were no significant interactions between these three factors.

In Condition 1 the WCI surface was enclosed. Condition 3 consisted of the identical WCI stimulus as a single surface of a three-dimensional object. Despite these two WCI regions being identical, the data suggest that simply being part of a stimulus with additional contours can impact the strength of color spreading. The perceived three-dimensionality may also have made an impact. The filling-in process taking place in an enclosed WCI stimulus may weaken in perceptual magnitude due to any number of factors, but it will not spread outside of the enclosed space. In Condition 2, one border of the WCI enclosure was removed which should have allowed the illusory color to spread into the newly opened area (i.e., Region 2). However, despite the removal of this physical border, color was not perceived beyond the original enclosed area (i.e., color did not spread from Region 1 into Region 2; see shading data on the heat maps in Figure 12). This finding supports our hypothesis that global configuration is an important factor in how color spreading illusions manifest. The visual system seems to be unconsciously dividing the unenclosed area into two distinct parts and only filling-in color for the part that is surrounded primarily by WCI fringe. If perceptually organized as two parts, the second part does not contain any information that would cue the visual system to fill it in with color. This results in a faint illusory color contour between Regions 1 and 2. Interestingly, the illusory color contour generated by the perceptual organization of the unenclosed WCI region into two surfaces may be considered sufficient as a border by the mechanisms responsible for color spreading illusions like this. Therefore, this stimulus is not being treated by the visual system as an unenclosed region at all but rather as two enclosed regions with an illusory border separating them. In Condition 4, Regions 1 and 2 are perceived as separate sides of the three-dimensional shapes. We hypothesized the color would fail to spread “around the corner” from the front surface to the side surface in this condition because of this. This manipulation was apparently unnecessary however since we achieved the same result in the two-dimensional configurations in Condition 2. Therefore, three-dimensionality does not seem to be a necessary factor in stopping color spreading. This seems fairly logical however since a single flat surface in the real world can contain multiple parts of differing color, texture, and brightness. It would be advantageous to be able to perceptually organize, discriminate between, and fill-in these regions as quickly and appropriately as possible.

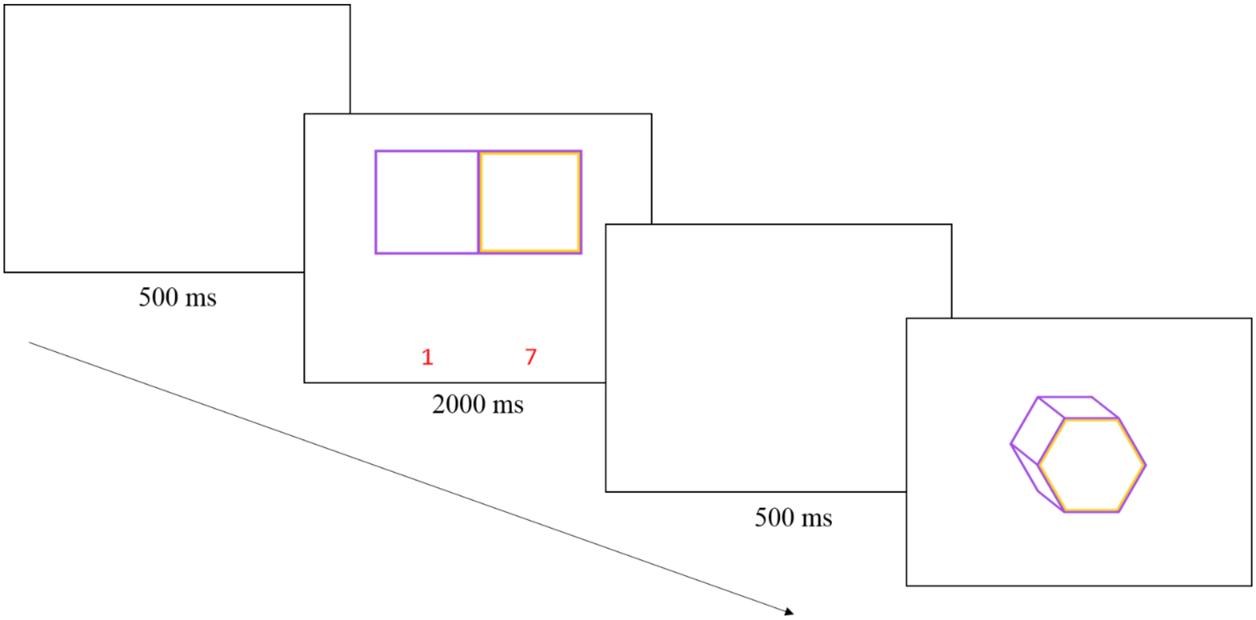

Figure 6. Example of a trial sequence. Each trial starts with a blank screen (500 ms) followed by a comparison stimulus (2000 ms), another blank screen (500 ms), and then the test stimulus which remained on screen until a response was entered. This example is from Experiment 1 Condition 3.

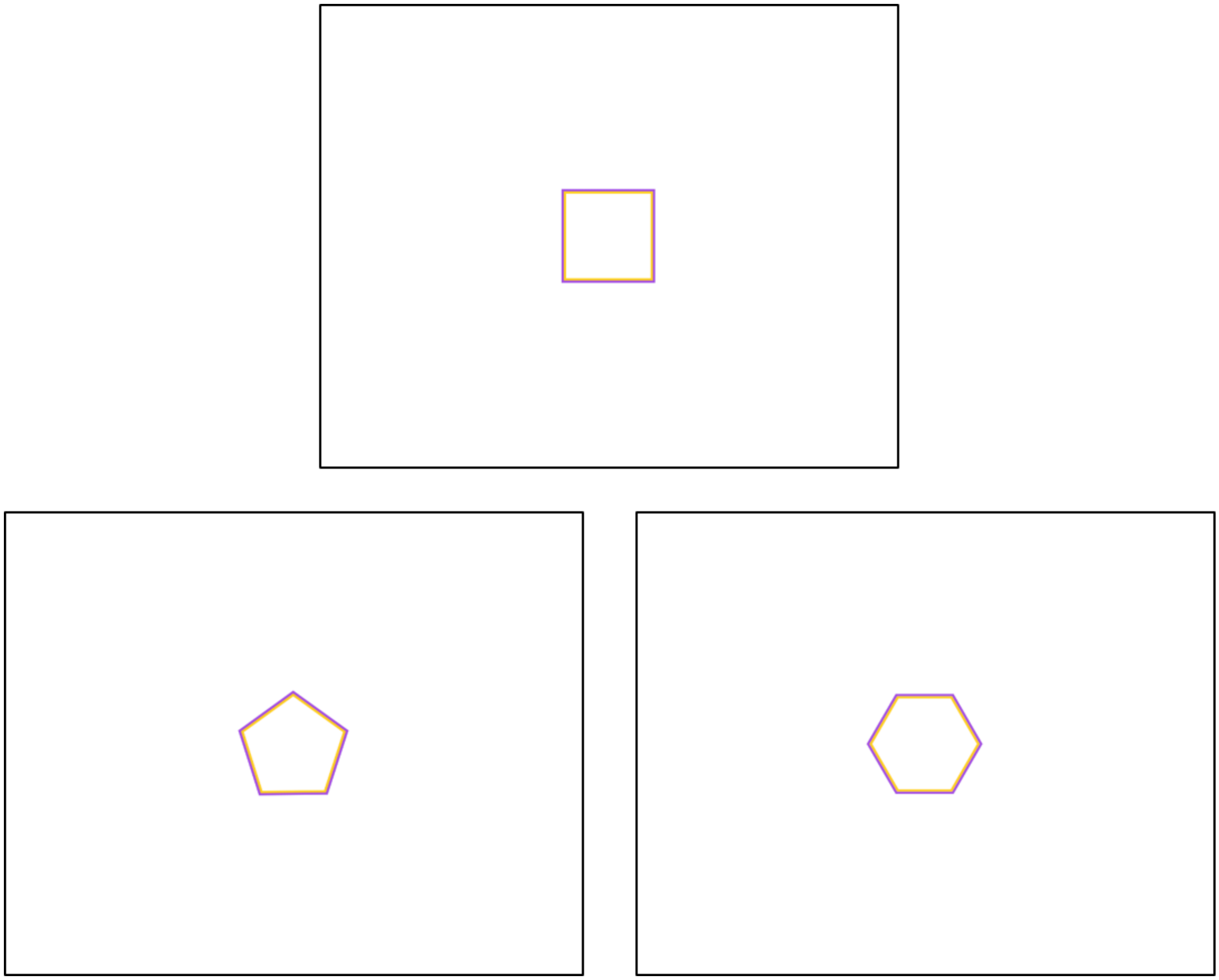

Figure 7. Baseline stimuli from Experiment 1, Condition 1 and Experiment 2, Condition 1 consisting of three centrally located two-dimensional shapes (i.e., square, pentagon, and hexagon) on a white background. Black outline around figure (and all other stimuli figures) represents screen size and was not actually present.

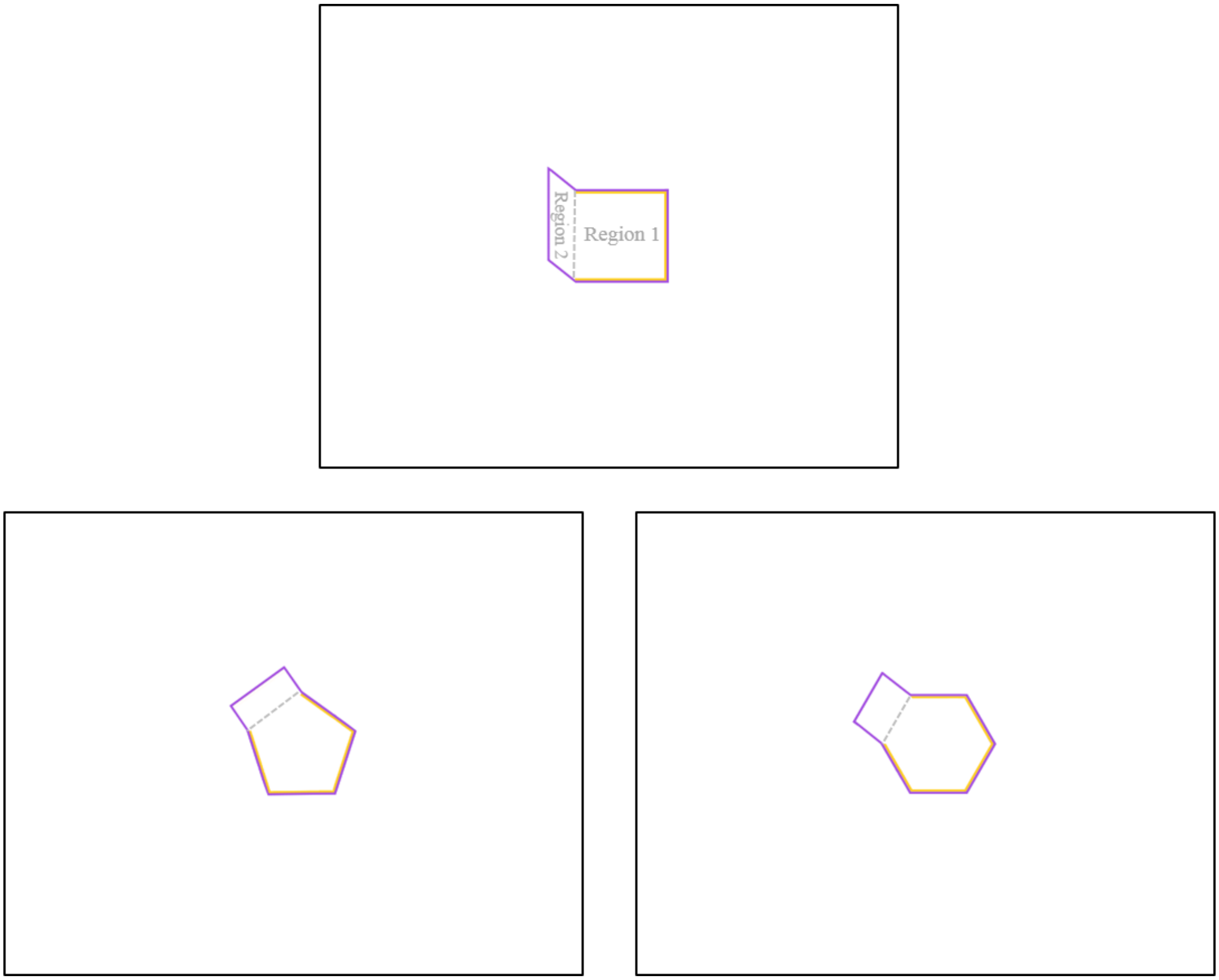

Figure 8. Stimuli from Experiment 1, Condition 2 consisting of three possible two-dimensional shapes on a white background. Region 1 and 2 and dashed lines are for illustration purposes and were not visible during the experiment.

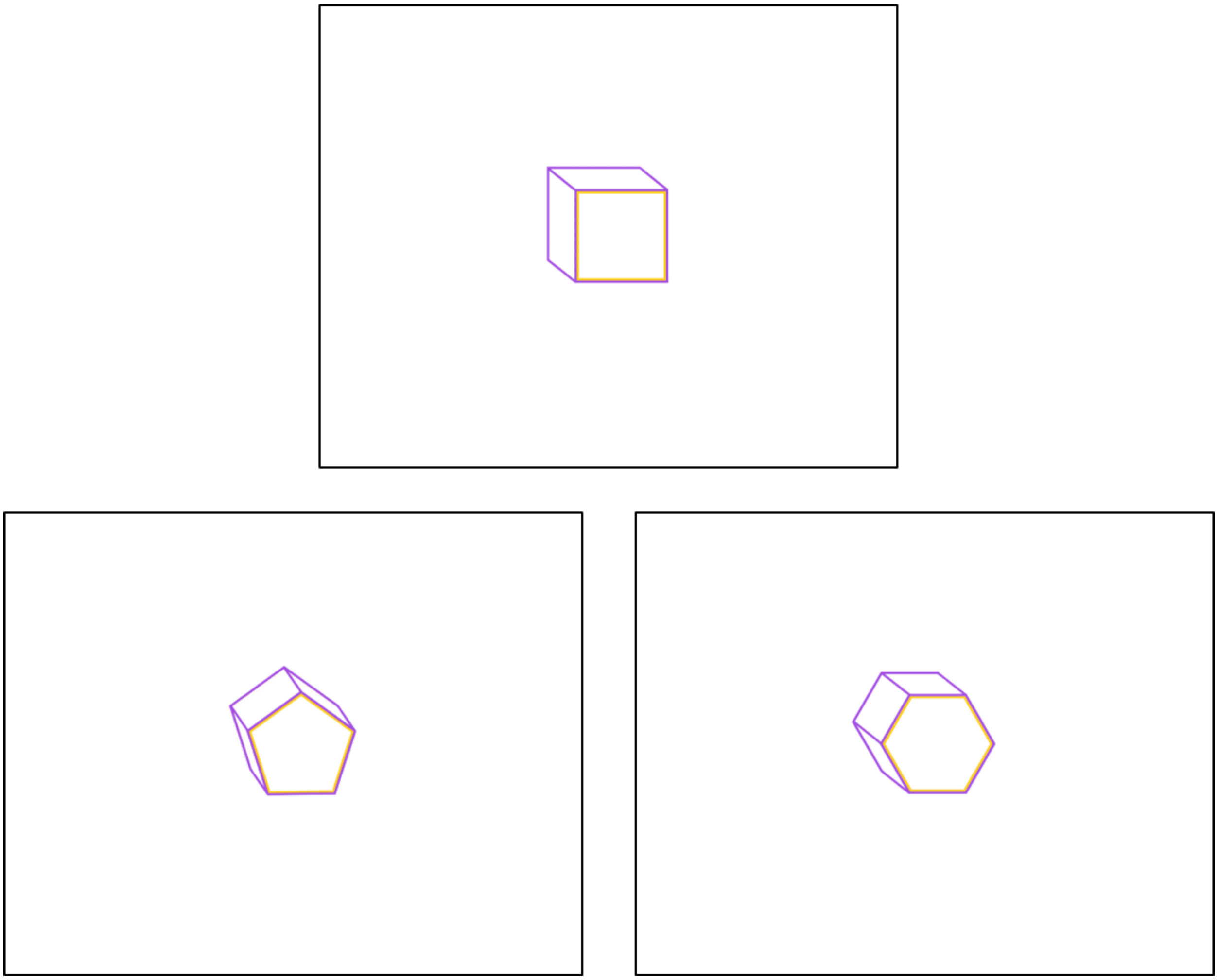

Figure 9. Stimuli from Experiment 1, Condition 3 consisting of three centrally located three-dimensional shapes (i.e., cube, pentagonal prism, and hexagonal prism) on a white background.

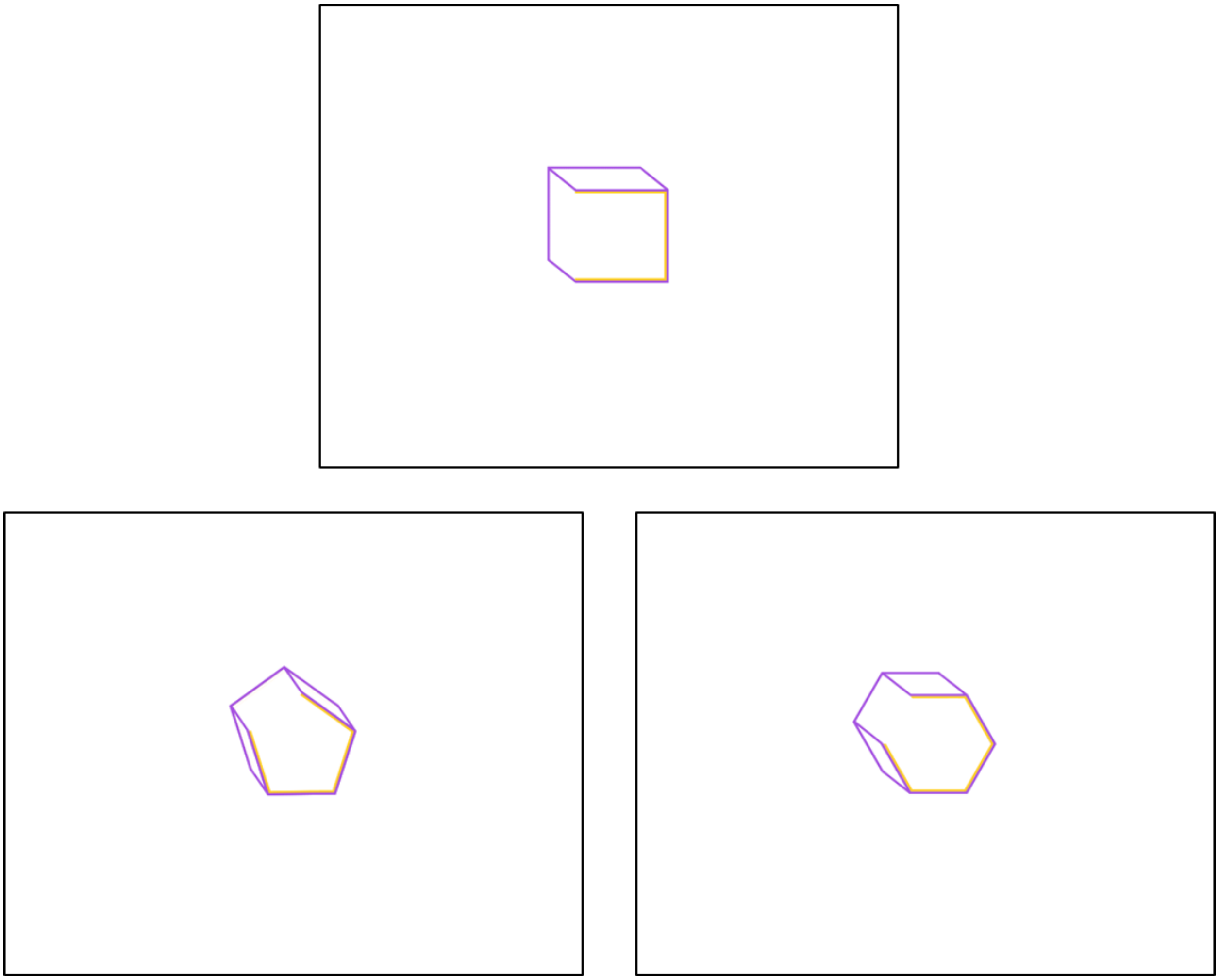

Figure 10. Stimuli from Experiment 1, Condition 4 consisting of three centrally located three-dimensional shapes (i.e., cube, pentagonal prism, and hexagonal prism) missing one “outer” contour and inner fringe on a white background.

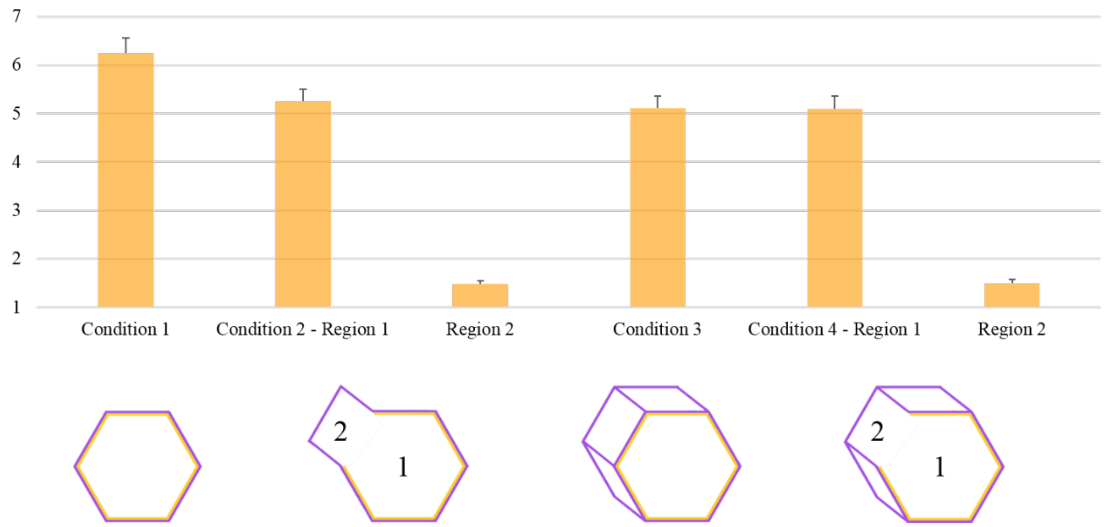

Figure 11. Illusion magnitude data collapsed across Shape for Experiment 1, Conditions 1 – 4. Only Conditions 2 and 4 had two ratings (i.e., Region 1 and Region 2). Example stimuli shown beneath each Condition.

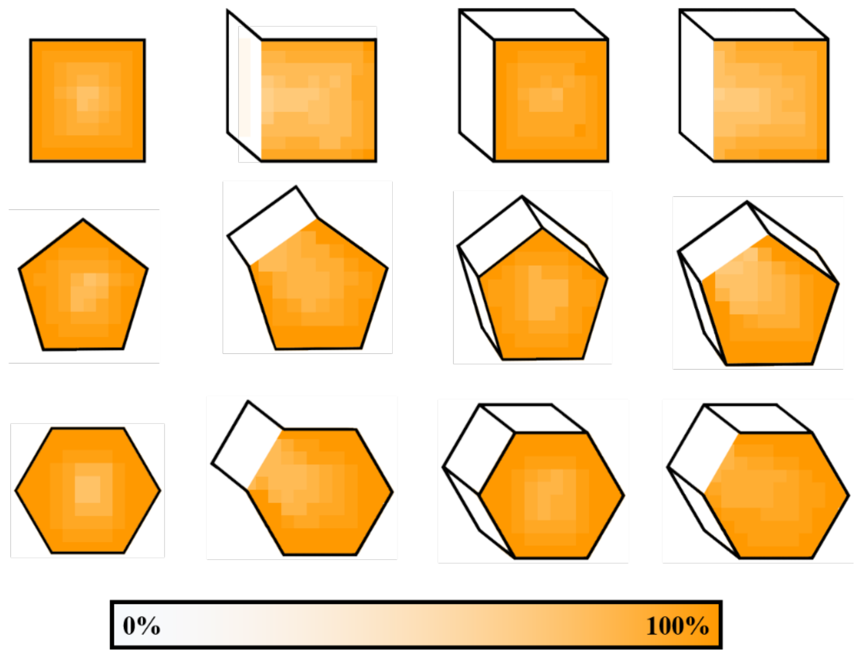

Figure 12. Participants shaded line drawings of the stimuli viewed following each condition. This data was averaged across individuals for each stimulus, and a conditional formatting grid was used to create these heat maps as an approximated visual display of this data. As indicated by the scale below the heat maps, a darker, more saturated orange correlates with a higher percentage of individuals shading this region. These heat maps are not representative of how hard or light someone shaded but rather the percentage of individuals who shaded a particular area. From left to right these columns of heat maps are for Conditions 1 – 4, respectively.

Table 1: Two-dimensional vs three-dimensional rating pilot data for Experiment 1 and 2 stimuli.

	Experiment 1					Experiment 2			
	“A”	“B”	“C”	Avg.		“A”	“B”	“C”	Avg.
C1	1	1	1	1	C1	1	1	1	1
C2	**2.71**	**1.28**	**1.14**	**1.71**	**C2**	**3.71**	**3.71**	**4.14**	**3.86**
C3	6.86	6.86	6.86	6.86	**C3**	**4.86**	**3.43**	**3.57**	**3.95**
C4	6.86	6.86	6.86	6.86	C4	7	7	7	7
					C5	7	7	7	7
					C6	7	7	7	7
					C7	7	7	7	7

Note: Ratings are averaged across seven pilot subjects who rated the depthfulness of each stimulus on a Likert-type scale from 1-7 where “1” was two-dimensional/flat and “7” was three-dimensional/depthful. Shape “A” refers to the squares, cubes, and chevron-like shapes. Shape “B” refers to the pentagons, pentagonal prisms, and other shapes associated with pentagons. Shape “C” refers to the hexagons, hexagonal prisms, and other shapes associated with hexagons. The row labels (e.g., C1) represent condition numbers. The conditions of interest are shown in bold.

Table 2: Condition Breakdown for Experiments 1 and 2

	Description	Stimuli	Purpose	Comparisons
Experiment 1	*"Solid/Opaque 2D & 3D"*			
Condition 1	Standard 2D shape		Magnitude & baseline for C3	C1 vs C2 - 3
Condition 2	2D partial baseline		Baseline for C4	C2 vs C4
Condition 3	3D complete object		Optimal 3D version	C3 vs C4
Condition 4	3D partial object		Does color spread around the corner?	See above
Experiment 2	*"Wire Frame (WF) 2D & 3D"*			
Condition 1	Standard 2D shape		Magnitude baseline	C1 vs C2
Condition 2	Transparent 2D shape		Baseline for C4	C2 vs C4
Condition 3	Transparent 2D partial baseline		Baseline for C5	C3 vs C5
Condition 4	3D complete object		Optimal 3D version	C4 vs C5 - 7
Condition 5	3D partial object		Does color spread around the corner?	See above
Condition 6	3D complete object partial fringe		Will the fringe cross these contours?	C6 vs C7
Condition 7	3D complete object extended partial fringe		Will the fringe fill the front now?	See above

Note: This breakdown includes descriptions and images of stimuli, a basic explanation of the purpose for each condition, and planned pairwise comparisons for Experiments 1 and 2.

CHAPTER 4

EXPERIMENT 2

The difference between different types of illusory color spreading is largely due to stimulus configuration. Pinna and Grossberg (2005) demonstrates this with a traditional WCI stimulus atop a bipartite background which can be seen beneath the WCI figure (similar to Figure 3). A background that is divided into two different luminances viewable through the WCI region generates a perception of transparency. In doing so, this shifts the phenomenal experience of the color spreading from a more traditional WCI effect towards a perception more similar to NCS (i.e., a transparent colored veil). In Experiment 1 the surfaces and objects had the opaque solid quality normally associated with the WCI. In Experiment 2 we manipulated the stimuli from Experiment 1 to alter this perception. Although the seven conditions in Experiment 2 highly resembled those of Experiment 1, the shapes now appeared to be transparent line drawings or "wire frames" of these shapes.

Condition 1 in Experiment 2 will be identical to that of Condition 1 in Experiment 1, and Condition 1 ratings should not be statistically different from one another between Experiments 1 and 2 (see Table 2 for a complete breakdown of conditions, stimuli, and planned comparisons for Experiments 1 and 2). Condition 2 was identical to Condition 1 except these stimuli will be "transparent". That is, the contours that can be seen through Region 1 in subsequent three-dimensional conditions of this experiment due to stimulus transparency are also present in this more two-dimensional configuration (see Figure 13). This allowed us to begin determining what aspects of our stimulus configurations were driving any change in color spreading phenomenally. If differences exist between Condition 1 and Condition 2 this would suggest participants perceived these stimuli as a transparent film occluding a pattern of contours rather than the perception of multiple smaller shapes abutting to form the shape that constitutes Region 1.

Condition 3 was the final baseline required for this experiment. This condition was identical to Experiment 1, Condition 2 except it was also "transparent" as just described for Experiment 2, Condition 2 (see Figure 14). This provided a baseline condition to examine the perceived differences between Region 1 and Region 2 prior to examining these regions in a three-dimensional configuration. As mentioned in the previous condition, Condition 3 may also be perceived as an occlusion event due to the placement of the inner fringe in Region 1. The addition of Region 2 also provided context that could lead to a slightly more depthful perception. As with Experiment 1, these baseline conditions were tested first so participants' perceptions were not biased towards a more three-dimensional organization of the stimuli. Nevertheless the shapes used in Conditions 2 and 3 could still be perceived to be somewhat three-dimensional by some participants. Pilot data revealed an increase in depthfulness for baseline conditions from Experiment 1 to Experiment 2 (see Table 1). Using a Likert-type scale from 1 – 7 where "1" was two-dimensional/flat and "7" was three-dimensional/depthful, the average rating was a 3.86 for all stimuli in Condition 2 and a 3.95 in Condition 3 compared to a 1.71 in Experiment 1, Condition 2. While this was significantly less than the "full depth" conditions in either experiment (i.e., Conditions 3 – 4 in Experiment 1 and Conditions 4 – 7 in Experiment 2), it still shows an increase in depthfulness due to the transparent nature of these baseline stimuli in Experiment 2.

The baseline configurations in Condition 2 were compared to the pictures of three-dimensional wireframe objects in Condition 4 (see Figure 15). These objects were identical to those in Experiment 1, Condition 3 except these objects appeared to be hollow wireframes rather than solid objects with opaque surfaces. Nevertheless the color spreading in Region 1 still occurs. Therefore this surface must appear transparent to accommodate this occlusion event thus allowing the observer to see through the front surface to the other surfaces that were hidden in Experiment 1. This condition should elicit the highest illusion magnitude of any three-dimensional configurations in this experiment. Despite this, as a transparent surface the illusion magnitude is likely to be less than that of the opaque three-dimensional complete objects from Experiment 1. In fact this is likely to be true for all analogous pairs between the solid (i.e., Experiment 1) and wireframe (i.e., Experiment 2) configurations. This is why having an identical baseline (i.e., Condition 1), and identical comparison stimuli (see Figure 6) for both experiments is so important. We can directly compare illusion magnitudes between experiments because they both used the same baseline for this measure.

Condition 5 was the wireframe version of Experiment 1, Condition 4 (see Figure 16). This condition began a more complex exploration of color spreading in pictures of ambiguous three-dimensional configurations that continues in the subsequent conditions. As with the solid versions of these objects in Experiment 1, a faint illusory color contour may exist between Regions 1 and 2.

In all of the conditions to this point the illusory color was expected to traverse a plane in space perceived to be the foremost surface of an object. In other words it is more likely that an observer may perceive the hexagonal prism from Condition 4 as a wireframe object with a transparent orange front surface than as a wireframe object with no front surface and four partial orange surfaces. Both of these organizations are possible. However the first is much simpler and therefore more likely. Consequently the visual system automatically organizes the information this way. In fact this perception is so preferred it is nearly impossible to perceive the stimulus as four orange regions all approaching intersecting contours instead of one continuous orange surface in front of these other contours. This is not to say that these objects themselves are not reversible. The wireframe cube is essentially a Necker cube with an orange front surface (Kornmeier & Bach, 2005). With minimal effort this impression can be switched to an upward facing Necker cube with an orange back surface. However the strong figurality commonly associated with the WCI is able to keep this reversibility to a minimum in favor of the WCI region in the foreground (Pinna, 2005).

Another factor contributing to an orange front surface being the preferred interpretation was the amount of orange fringe inside of Region 1. In Condition 6 we reduced the amount of orange fringe from the complete wireframe object condition (i.e., Condition 4) in such a way that it stopped whenever it reaches an abutting contour in either direction. This therefore subdivided Region 1 into Region 1A (i.e., the fringed region) and Region 1B (i.e., the non-fringed region; see Figure 17). This fringe reduction may reduce illusion magnitude across the entirety of Region 1 if participants still perceive this region to be the colored transparent surface as in the previous condition. However due to this new configuration the participants may now perceive part of the right side of the cube visible in Region 1A as the color surface and perceive the rest of the object as a simple wireframe. This should strengthen the illusion magnitude in Region 1A while reducing or eliminating the illusion in 1B. From a lower level and more local processing perspective, the color may not spread past the contours that enclose Region 1A because the fringe does not extend past this Region. This local processing may then affect the more global perception of the object as mentioned above.

Based on the hypothesized outcome for Condition 6 more information is likely necessary for the color to spread beyond the enclosed 1A region. In Condition 7 we extended the fringe

0.5° of visual angle in both directions using the otherwise identical stimuli from Condition 6 (see Figure 18). Now that the fringe extends further past Region 1A into Region 1B, color should spread into all of Region 1 returning to the perception of an orange front surface of the wireframe object as in Conditions 4 and 5. However the illusion magnitude may be weaker due to the fringe reduction compared to Condition 5 with missing, yet more fringe, and the completed fringe version in Condition 4.

Altogether this experiment explored a more complex assortment of pictures of two-dimensional and three-dimensional stimulus configurations to examine what effect these contextual factors have on color spreading. These wireframe surfaces and objects were compared to their solid counterparts from Experiment 1 to determine what effect this new layer of complexity has on this phenomenon.

Experiment 2 Method

Stimuli. Eight sets of three stimuli were created for Conditions 1 – 7. Stimuli for Condition 1 were identical to Experiment 1. Condition 2 consisted of the same pictures of two-dimensional shapes as Condition 1 with the addition of any contours present within these shapes (i.e., Region 1) in the three-dimensional wireframe versions. Condition 3 consisted of Regions 1 and 2 and the additional contours described in Condition 2 (i.e., those that were visible in the shape in the three-dimensional version). Condition 4 consisted of three-dimensional wireframe versions of the figures from Condition 1 with fringe in only the foremost surface (i.e., cube, pentagonal prism, hexagonal prism). The cube, pentagonal prism, and hexagonal prism now all fit within a region subtending 2.80° of visual angle to accommodate their three-dimensional size. Stimuli for Condition 5 were identical to Condition 4 except one side (including the outer contour and inner fringe) of the surface containing the WCI fringe was removed. Stimuli for

Condition 6 were identical to Condition 4 except the fringe only extended to the points at which it crosses an abutting contour now visible due to the wire frame configuration. Condition 7 was identical to Condition 6 except the fringe will extend 0.50° of visual angle into Region 1B.

Design and Procedure. The design and procedure was identical to Experiment 1. For Conditions 6 and 7, the two ratings recorded were for Regions 1A and 1B rather than Regions 1 and 2. This did not alter the procedure however.

Experiment 2 Results and Discussion

A 7 (Condition) x 3 (Shape) within-subjects ANOVA was conducted to analyze the hypotheses laid out in Experiment 2 using the Region 1 magnitude estimation data only. As in Experiment 1, the purpose of having three different shapes was to ensure our findings were not due to the specific configuration of any one of them and so, a main effect of Shape was not expected. A main effect of Condition was expected due to the anticipated weakening of the WCI in the spreading region once a border has been removed (i.e., Condition 5 and potentially Condition 3) and when a partial fringe exists (i.e., Conditions 6 and 7). Condition 1 should also be different than the remaining conditions since it was the only non-transparent condition. There was a significant main effect of Condition, $F(6,294) = 4.909$, $p < .001$, no main effect of Shape, $F(2,294) = .199$, $p = .820$, and no significant interaction, $F(12,168) = .523$, $p = .900$ (see Figure 19). As noted in Table 2, there were additional planned pairwise comparisons between conditions. As predicted, Condition 1 had significantly higher ratings than all six remaining conditions as the only non-transparent condition, $p \leq .025$. This supports the notion that increased stimulus parts/contours both within a color spreading region (local) and around the color spreading region (global) can negatively impact illusion magnitude. Condition 2 was intended to be a two-dimensional control for the Condition 4. These two conditions were not statistically different from one another, $p = .248$. This is consistent with the similar results from Experiment 1 in which Condition 2 and Condition 4 were not statistically different. The surrounding three-dimensional structure did not alter the illusion magnitude. The same was also true for Condition 5 compared to its baseline condition (i.e., Condition 3), $p = .869$. Interestingly, there were no statistically different pairwise comparisons between any combination of Conditions 4 – 7, $p \geq .210$, indicating no differences exist between these conditions despite the removal of one border in Condition 5 or the reduction in fringe in Conditions 6 and 7.

The relative difference in illusion magnitude between Region 1 and Region 2 in Conditions 3 and 5 is also informative in regard to how this illusion manifests in stimulus configurations more representative of our three-dimensional world. Therefore, a 2 (Condition) x 3 (Shape) x 2 (Region) within-subjects ANOVA was conducted. A main effect of Condition was predicted but did not exist, $F(1,168) = .032$, $p = .858$, suggesting that participants had a similar visual experience for two-dimensional (i.e., Condition 3) and three-dimensional (i.e., Condition 5) versions of the combined area inside Regions 1 and 2. This is confirmed by the statistically significant main effect of Region, $F(1,168) = 426.504$, $p > .001$, and is consistent with Experiment 1 in terms of Region 1 and 2 in Condition 2 and 4. Also consistent with Experiment 1, there was not a significant main effect of Shape, and there were no significant interactions between these three factors.

Additionally, a 2 (Condition) x 3 (Shape) x 2 (Region) within-subjects ANOVA was conducted to compare Regions 1A and 1B in Conditions 6 and 7. We predicted color would not spread from Region 1A to Region 1B in Condition 6 but that it would spread to Region 1B in Condition 7 due to the extension of the fringe. This predicted interaction was not supported however, $F(1,168) = .021$, $p = .884$. Instead, there was a significant main effect of Region, *F*(1,168) = 335.054, *p* = < .001, indicating that color failed to spread from Region 1A to Region 1B in either condition. There was no main effect of Shape, and the other potential interactions were also non-significant.

Condition 1 of Experiments 1 and 2 were identical in order to have a baseline comparison between these two groups of subjects. An independent-samples *t*-test confirmed that these subjects were not statistically different in their magnitude estimation ratings, *t*(28) = .071, *p* = .262. The first four conditions of Experiment 1 and Conditions 2 – 5 of Experiment 2 were identical except for the perceived solid versus wireframe configurations. Therefore a 2 (Experiment) x 5 (Condition) x 3 (Shape) mixed-subjects ANOVA was conducted to analyze the differences between these two experiments. We hypothesized a main effect of Experiment due to the solid nature of the illusion in Experiment 1 compared to the veil-like color spreading with the wireframe versions in Experiment 2. As the Conditions and Shapes are the same for these experiments, we expected to find a main effect of Condition and no main effect of Shape. Interestingly, despite the differences between these two experiments no main effect of Experiment was found, *F*(1,336) = 2.241, *p* = .135. This could simply be attributed to a reduction in the visibility of differences between experiments once the data was collapsed across Conditions except for the fact that it was echoed in the planned comparisons between experiments from Table 2. No statistical differences existed when comparing Condition 3 in Experiment 1 to Condition 4 in Experiment 2, *t*(14) = -.912, *p* = .377, or comparing Condition 4 in Experiment 1 to Condition 5 in Experiment 2, *t*(14) = -.459, *p* = .653. As predicted there was a main effect of Condition, *F*(3,336) = 4.132, *p* = .007, and no main effect of Shape, *F*(1,336) = .696, *p* = .499. There were no significant interactions between these factors.

An exploration of the findings from Experiment 2 alone supports our hypothesis that additional parts/contours within (local) and around (global) the color spreading region and perhaps implied three-dimensionality can negatively impact illusion magnitude. Phenomenologically the color spreading across the WCI surface of the stimuli in Conditions 2 – 6 more closely resembles that of NCS than traditional WCI. In other words, the color that fills in the color spreading region appears to be a hazy transparent film rather than an opaque solid. As with Experiment 1, color does not spread into a second region when there is a simple way to perceptually organize the surface into two distinct surfaces. This is most interesting in Condition 7. The fringe in this condition stops at an arbitrary point along the inside of the front surface of each object. This fringe does not share any end point with any other junction, end point, or feature change. Nevertheless color does not spread past the fringe. Most participants still reported a distinct stopping point for the observed color spreading between Regions 1A and 1B as can be seen in the shaded heat maps on Figure 20. The fact that all of the stimuli used for Experiments 1 and 2 use straight contours and basic shapes may lend itself to easier perceptual dissection (i.e., perceptually organizing a surface into more than one distinct surface). A straight contour can be drawn between the end points of the fringe in Condition 7 to create two parts that fit together side-by-side thus creating a multipart front surface of each object. This would be analogous to a stained glass window or a quilted blanket. The two surfaces are on the same plane, but they were distinctly individual. Therefore, the color logically would not spread into the neighboring region. This seems to be true for all “unenclosed” conditions, including those without a border (i.e., Conditions 2 and 4 in Experiment 1 and Conditions 3 and 5 in Experiment 2) and those with reduced fringe (i.e., Conditions 6 and 7 in Experiment 2). Participants primarily observed color spreading in the original color spreading region only (see Figures 12 and 20). This differs from the unenclosed serpentine WCI stimulus discussed previously (see

Figure 4A) simply due to the configural nature of the stimuli. Therefore, these experiments support our hypothesis that global context – including context more representative of the three-dimensional world – can impact the manifestation of illusory color spreading. Experiment 3 will seek to further this investigation by manipulating WCI stimuli more typical of previous WCI research.

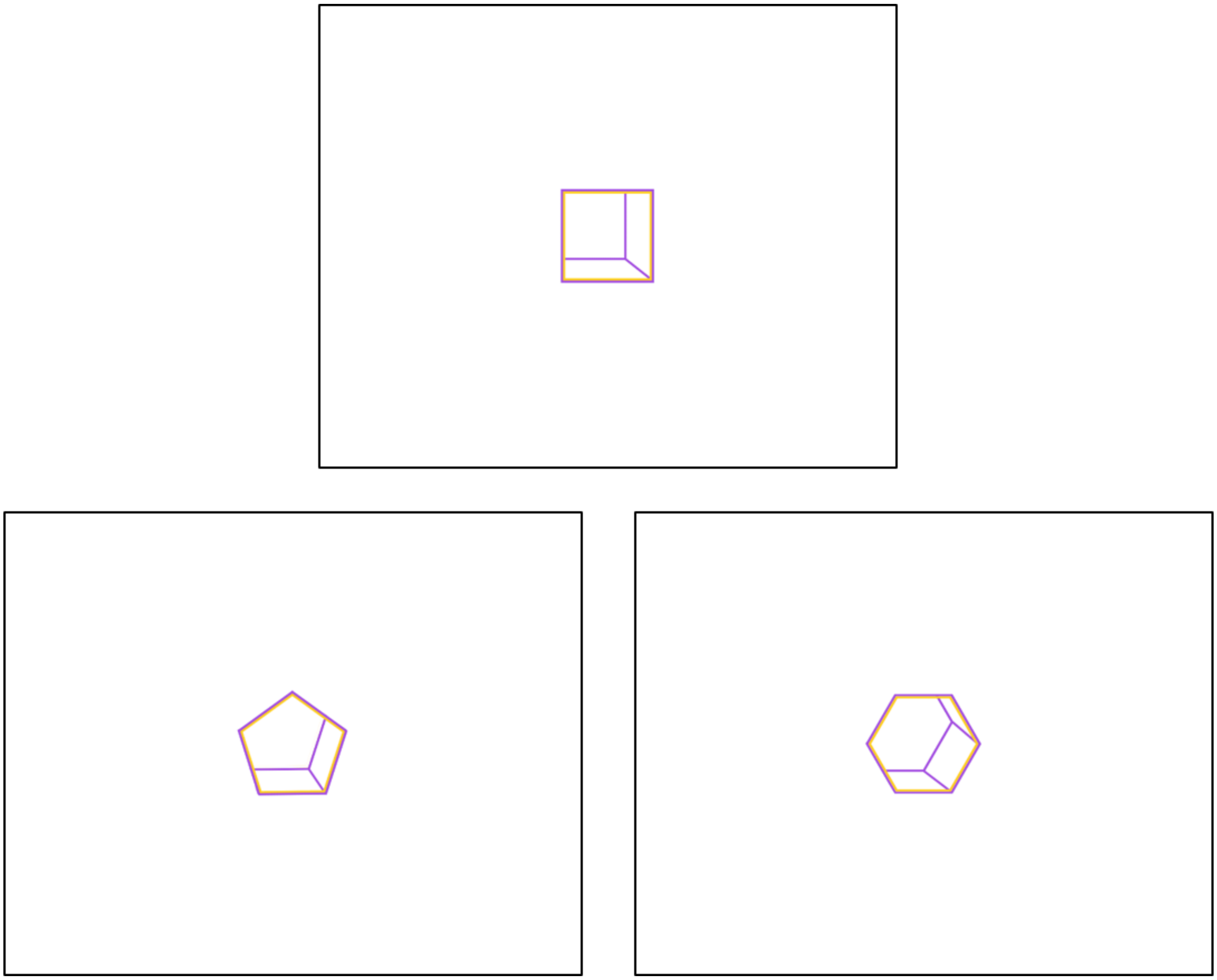

Figure 13. Stimuli from Experiment 2, Condition 2 consisting of three centrally located shapes (i.e., square, pentagon, and hexagon) with the enclosed contours from Experiment 2, Condition 4 present.

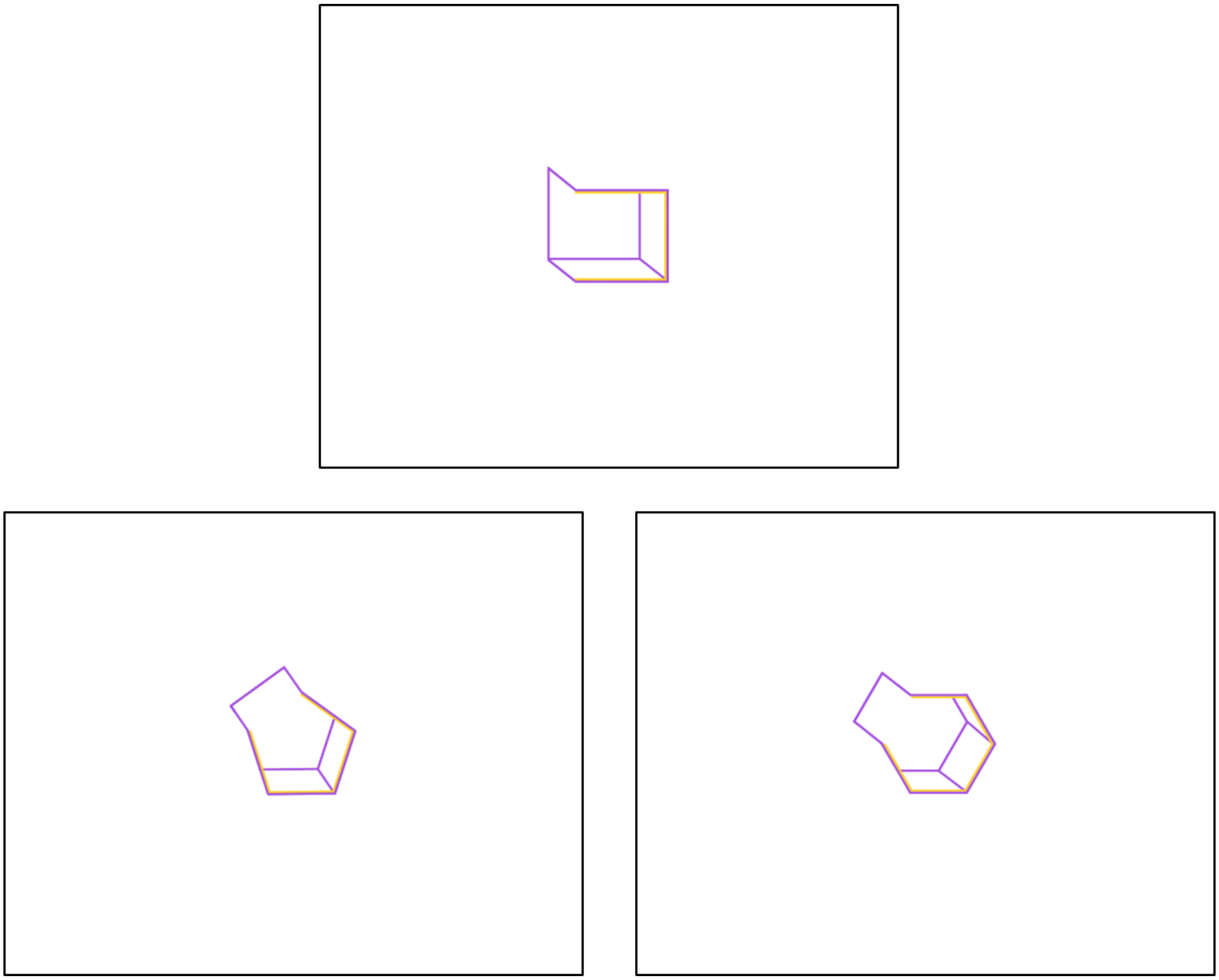

Figure 14. Stimuli from Experiment 2, Condition 3 consisting of three centrally located shapes with the enclosed contours from Experiment 2, Condition 4 present.

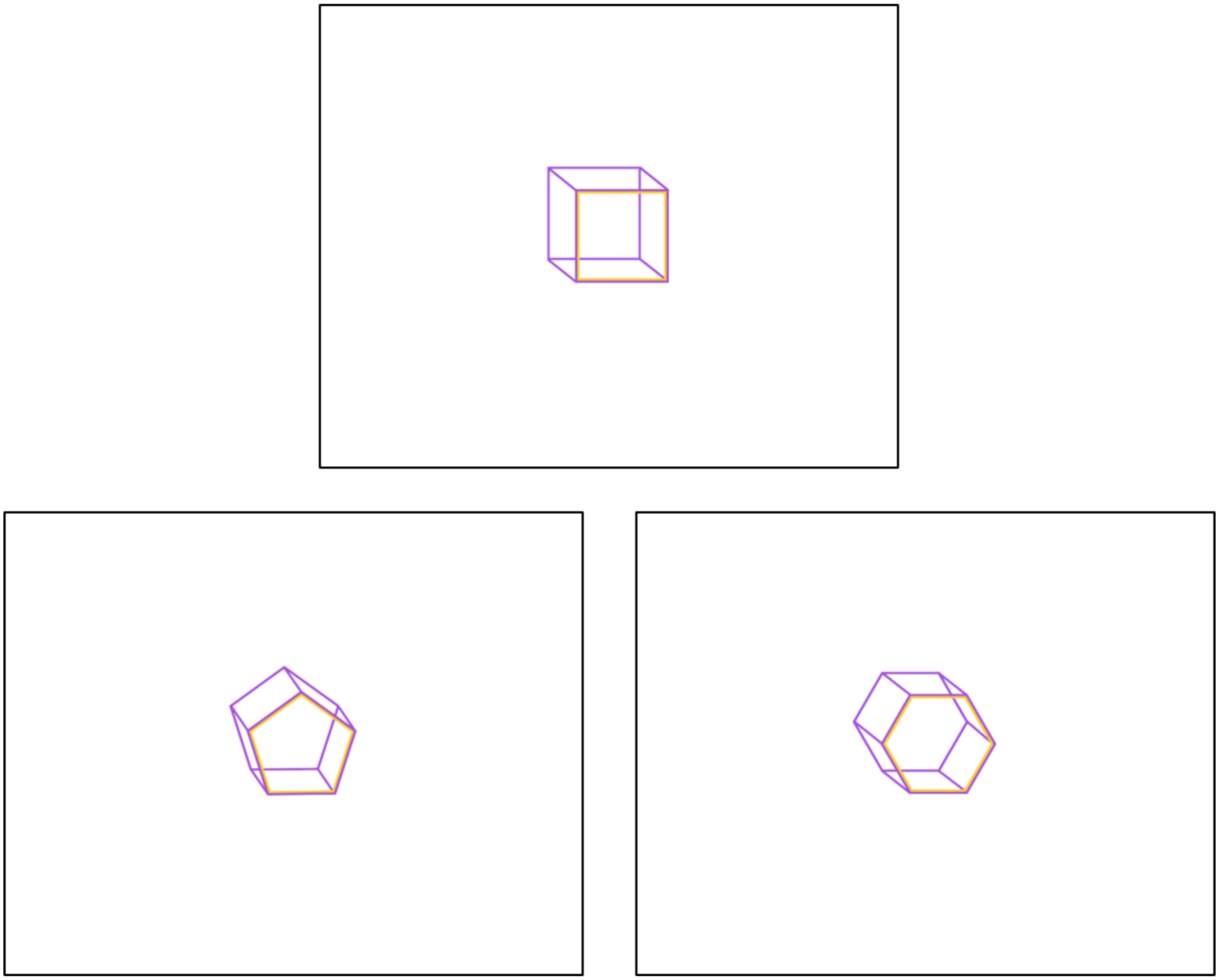

Figure 15. Stimuli from Experiment 2, Condition 4 consisting of three centrally located wire frame three-dimensional shapes (i.e., cube, pentagonal prism, and hexagonal prism) on a white background.

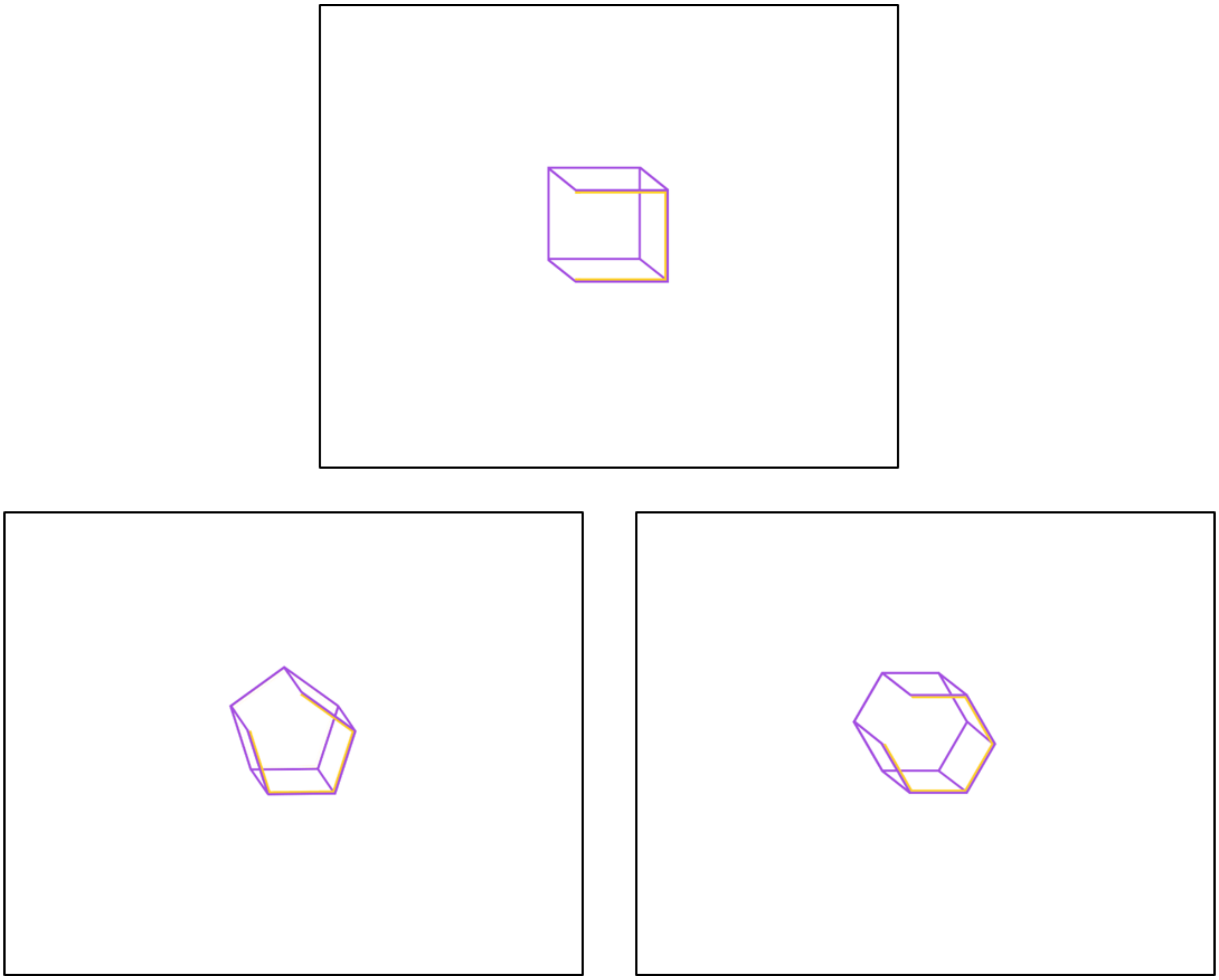

Figure 16. Stimuli from Experiment 2 Condition 5 consisting of three centrally located wire frame three-dimensional shapes (i.e., cube, pentagonal prism, and hexagonal prism) missing one “outer” contour and inner fringe on a white background.

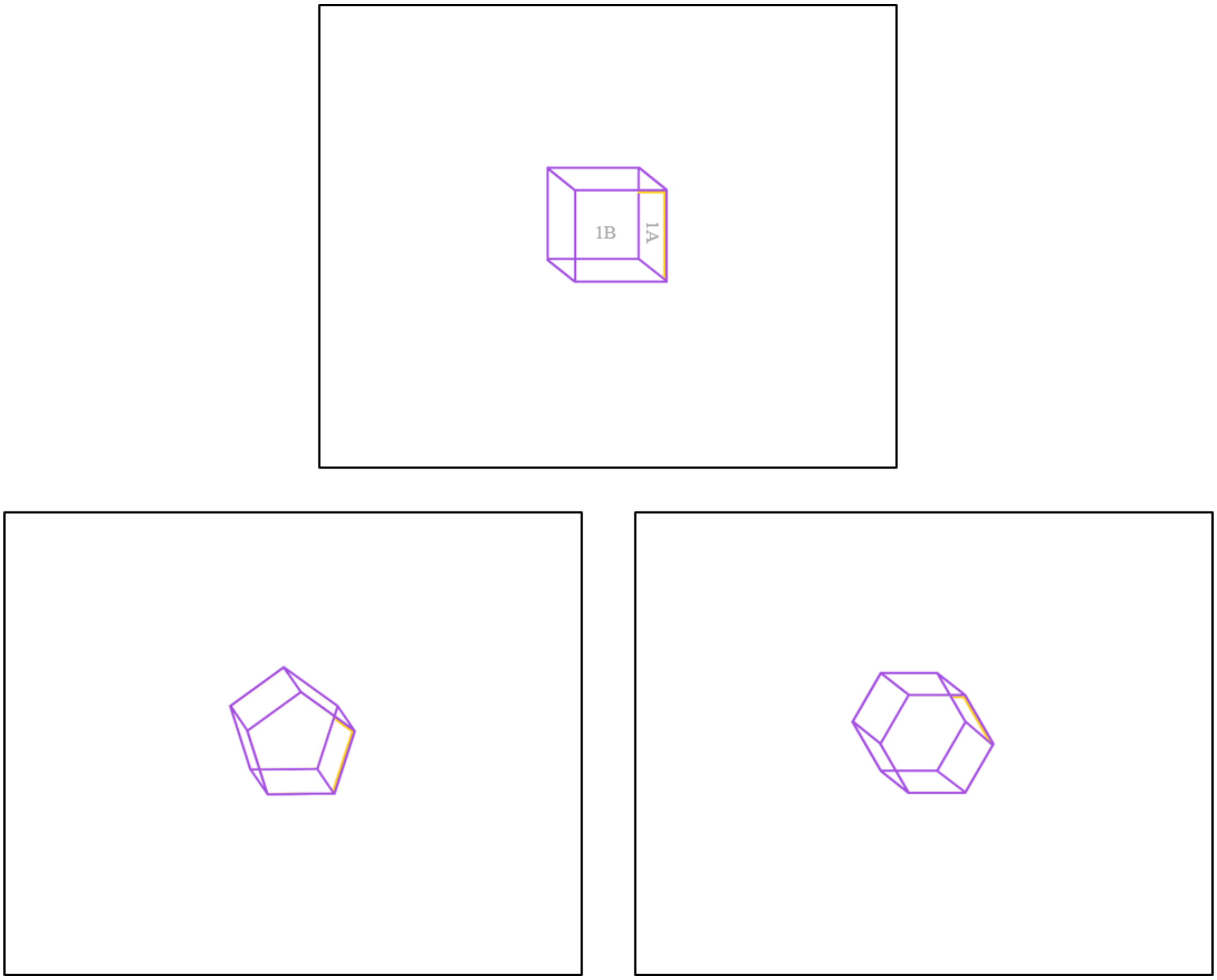

Figure 17. Stimuli from Experiment 2 Condition 6 consisting of three centrally located wire frame three-dimensional shapes (i.e., cube, pentagonal prism, and hexagonal prism) on a white background with fringe in only one section of the foremost surface.

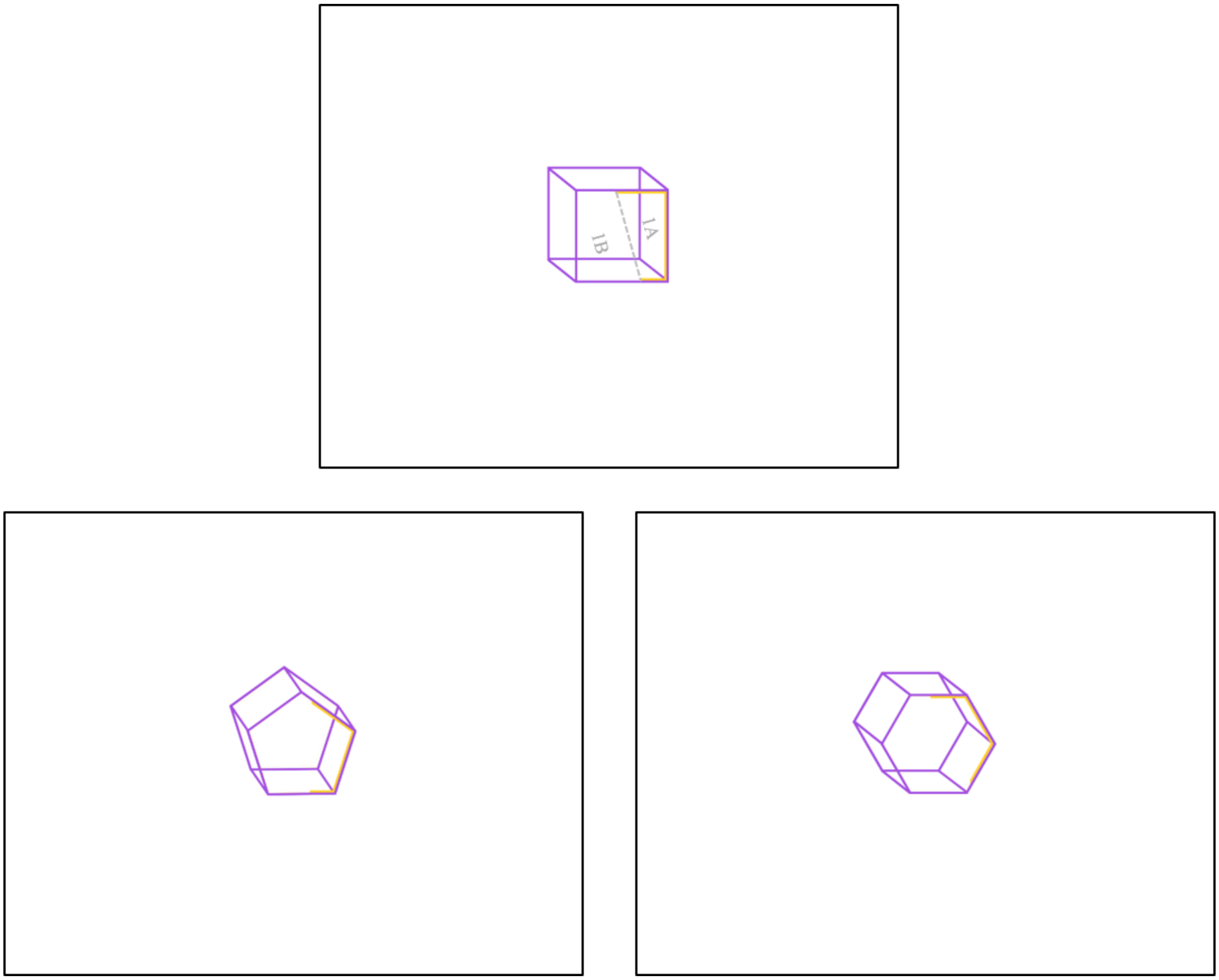

Figure 18. Stimuli from Experiment 2, Condition 7 consisting of three centrally located wire frame three-dimensional shapes (i.e., cube, pentagonal prism, and hexagonal prism) on a white background with partial fringe extending into foremost surface beyond the first abutting contours in either direction.

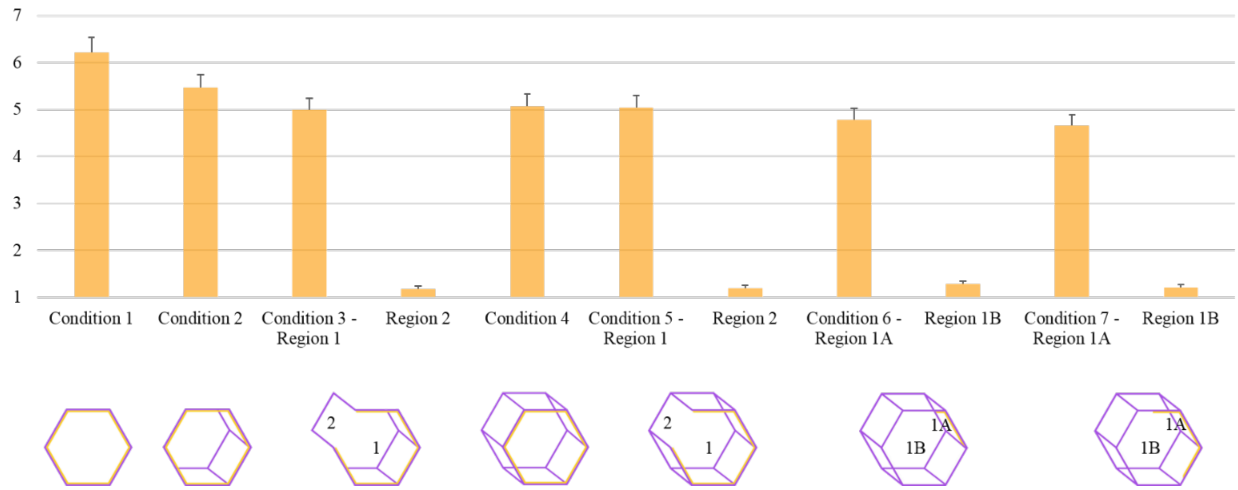

Figure 19. Illusion magnitude data collapsed across Shape for Experiment 2, Conditions 1 – 7. Conditions 3, 5, 6, and 7 had two ratings (i.e., Region 1 and Region 2 in Conditions 3 and 5; Regions 1A and 1B in Conditions 6 and 7). Example stimuli shown beneath each Condition.

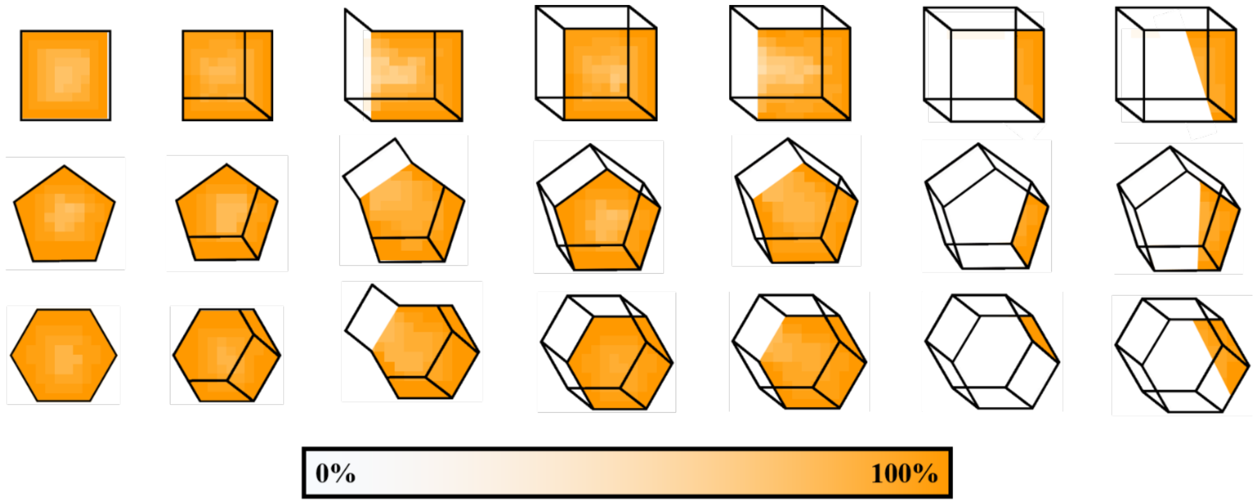

Figure 20. Participants shaded line drawings of the stimuli viewed following each condition. This data was averaged across individuals for each stimulus, and a conditional formatting grid was used to create these heat maps as an approximated visual display of this data. As indicated by the scale below the heat maps, a darker, more saturated orange correlates with a higher percentage of individuals shading this region. These heat maps are not representative of how hard or light someone shaded but rather the percentage of individuals who shaded a particular area. From left to right these columns of heat maps are for Conditions 1 – 7, respectively.

CHAPTER 5

EXPERIMENT 3

In the previous two experiments we demonstrated it is possible to stop WCI spreading when configural factors more representative of our three-dimensional world are present. For instance, the illusory color contour perceived along a missing border was likely due to the perceived organization of that particular stimulus (e.g., a two part shape). The illusory color contour then served as the border at which color ceased to spread. This created colored surfaces consisting of a combination of real borders, illusory borders, and illusory color spreading.

This experiment sought to determine if more traditional two-dimensional WCI stimuli (e.g., Figure 2) could elicit a similar interruption to color spreading by manipulating the global configuration. Research in this field thus far indicates color spreading will continue well beyond a WCI region if there is no border to stop the spreading; although the color saturation will degrade uniformly for increasingly larger spreading areas (Devinck et al., 2005; Pinna, 2011; Pinna et al., 2001; Pinna & Grossberg, 2005; Pinna & Reeves, 2006, 2015). In Figure 2B the outer orange fringe spreads to the entire page surrounding the stimulus thus supporting this claim. From an ecological perspective this long range spreading is the most logical interpretation and therefore manifestation of the illusion. In other words, the sheet of paper contains no configural cues to signal the color should cease to spread – nor does any other viable interpretation of the stimulus exist. Therefore, the color automatically spreads however weakly until it reaches the edges of the page. We have discussed in detail the serpentine configuration of a single wavy contour consisting of outer contour and fringe that Pinna and colleagues (2001) used to demonstrate how the WCI will spread within unenclosed spaces and beyond their borders (see Figure 4A). However, here too this spreading is the most logical interpretation of the stimulus. When the fringe is located on an inward facing section of a serpentine loop the color spreads into that region. Conversely when the outer contour faces inward in a loop color does not spread into this area. This leads to a stark perceptual contrast between these alternating regions. However, since all of these contours are part of one continuous contour that never intersect with one another or fully enclose a region, the illusory color that emanates from the fringe is able to diffuse outward beyond the borders of the physical stimulus.

In Experiment 3 we examined how basic WCI stimuli can be modified to elicit similar disruption to color spreading demonstrated in Experiments 1 and 2 in the absence of an enclosing border. This was done by creating new unenclosed stimuli that allowed for an alternative global interpretation. If the color spreads beyond the physical borders of our new stimuli then this would support the previous literature. However, if no color spreading occurs, this would indicate that global stimulus configuration can play an integral role in the outcome of filling-in mechanisms involved in illusory color spreading.

Condition 1 employed a centrally located large wavy square with a smaller wavy square inside. Similar to Figure 2A the fringe faced inward on the larger square and outward on the smaller square resulting in color spreading only inside the larger square until it reached the borders of the smaller square (see Figure 21A). This can be perceived as either an orange "doughnut" with a white hole in the middle or as an orange square with a white square on top or above it. The strong figurality cues attributed to the WCI and the object-hole effect suggest the first interpretation is most likely (Pinna & Tanca, 2008). The stimuli in Figure 21B – D show the WCI stimulus in 21A separated in space by increasingly larger increments as if cut into two parts along a central vertical axis. Similar to the missing border conditions of the first two experiments which made for a less optimal WCI stimulus, this modification to the stimulus is also likely to result in a reduction in illusion magnitude. As is the case with other unenclosed configurations from the WCI literature, the color was expected to spread beyond the WCI region containing the fringe now that the border that would otherwise stop the spreading had been removed. Alternatively, it was possible color spreading might be contained within the separated regions despite these incomplete enclosures depending on the perceived organization of the stimulus. If participants simultaneously perceive no color in the region between the two doughnut halves and do perceive color inside the doughnut regions, then implied color contours must exist similar to those found in Experiments 1 and 2. These contours would "belong" to the separated parts themselves as if they were two distinct horseshoe shapes. Alternately, the contours could belong to an occluding surface similar to a stationary visual phantom (Brown, Gyoba, & May, 2001; Brown & Weisstein, 1988; Kitaoka, Gyoba, Kawabata, & Sakurai, 2001; Tynan & Sekuler, 1975) or other illusory figures such as the Kanizsa triangle (Kanizsa, 1955; Von der Heydt, Peterhans, & Baumgartner, 1984) and the Ehrenstein illusion (Ehrenstein, 1941; Pinna, Ehrenstein, & Spillmann, 2004). This perception would result in a pair of vertical illusory contours which belong to a rectangular bar (i.e., visual phantom) rather than to the horseshoe shaped WCI regions giving the appearance of a still completed doughnut occluded by a vertical white bar. Whether participants view stimuli B – D as two separate shapes or one occluded shape could potentially depend on the distance between the two parts. For instance, given enough space between the two parts (e.g., Version D) the occluding phantom region may dissipate. This could result in either the color spreading remaining limited to the now two parts enclosed by smaller illusory color contours or the color spreading outside of these parts into the background as has been found for unenclosed WCI stimuli in the past. In summary, based on the results of

Experiments 1 and 2 we hypothesized illusion magnitude would be the greatest in Condition 1, Version 1 (See Figure 21A) and would decrease as separation between the two parts increased. We also hypothesized that the color would not spread outside of the doughnut region or horseshoe regions despite the missing physical borders. Instead these parts would likely be perceived as either two solid colored shapes or a single solid shape occluded by a white bar, and this perception might depend on the distance between the two parts.

Condition 2 was identical to Condition 1 except the top and bottom of the larger outer square was removed (see Figure 22). The left and right wavy contours were pointing outward at their ends to encourage color to spread outward. Additionally the fringe from the smaller square was no longer encumbered by the upper and lower constraints since these borders had been removed thus improving the likelihood of color spreading beyond the confines of the physical stimulus. As the stimulus was spread apart in B – D we would be able to observe how the area in between these separated parts was perceived given this new configuration. Despite the expectation of spreading beyond the stimulus based on previous literature, we hypothesized that the region between the two halves will be similar in appearance to Condition 1. The smaller central square was identical in both conditions providing what was likely to be sufficient context to induce this perception. Unlike the missing border conditions in Experiments 1 and 2 it was unlikely color would stop spreading out to an illusory color contour at the top and bottom in this condition. The color was also unlikely to spread continuously until it reached the edge of the display as it does in Figure 2B. Instead, due to the configuration of the stimulus we hypothesized that the color spreading would gradually degrade into the regions just outside of the now unenclosed parts, and this degradation would likely occur closer to the fringe as the parts spread farther away from one another. Color spreading from WCI stimuli has always been reported as emanating evenly across a surface (Pinna et al., 2001). Therefore the quick degradation expected here due to this configuration would potentially be a unique finding.

The third condition replaced the squares from the first two conditions with crosses with the same fringe configurations (see Figure 23). Rather than splitting the crosses in the center like the previous conditions, Condition 3 was split to the right of center for stimuli B and C. This resulted in a left-oriented "U" shape part on the right and the complete removal of the right outer borders on the left part. Version A should be identical in illusion magnitude in Condition 1 and Condition 3. However as the parts spread away from one another, previous literature would suggest differences should start to arise. Since the right part was significantly smaller than the left, it was unlikely to stop the now exposed outward facing fringe within the cross from spreading color across the separation and beyond. Similar to the upper and lower borders of Condition 2, the entire right side of the left part was open. The difference however was that another viable interpretation existed in this condition. Due partially to the "U" shaped region on the right, it still might be possible to perceive a phantom occluding region in the separation. This would result in zero spreading for both the left and right regions. Therefore Version D in this condition removed the right portion from B and C entirely. In this version the color was expected to gradually degrade outward from the stimulus in a similar fashion to Condition 2. However the multiple remaining border end points from the inner and outer crosses may still result in something similar to the perceptual occlusion event observed in previous stimuli.

Collectively these conditions were expected to test how global configural factors influence the spreading nature of the WCI using more traditional two-dimensional WCI stimuli by demonstrating that color may not always spread beyond stimulus borders into an open region as previously thought. The caveat here is that an illusory contour or surface of some kind may be necessary in order for the color to not spread. In this way one could argue that the WCI will spread to fill an enclosed region, and an illusory contour is sufficient to define the enclosure. Interestingly the strong figurality commonly associated with the WCI may be overcome slightly by the perception of an occluding visual phantom. This would be one of the first examples of a non-WCI region appearing as the foremost surface in a WCI display. The gradual degradation of color spreading expected in Conditions 1 and 2 are likely a byproduct of competition of some kind between the color spreading mechanisms attempting to spread and organizational mechanisms attempting to enclose these geometric parts. These global configurations should demonstrate the importance of examining color spreading illusions using more complex stimulus configurations to help us better understand their role in visual perception.

Experiment 3 Method

Stimuli. Three sets of four stimuli were created consisting of a centrally located larger outer shape with fringe facing inward and a centrally located smaller inner shape with fringe facing outward. For Conditions 1 (Figure 21) and 2 (Figure 22) the outer shape (i.e., squares) subtended an area of 4.87° (height) × 4.87° (width) and the inner shape subtended an area of 2.67° (height) × 2.67° (width). The cross shapes for Experiment 3 (Figure 23) were larger to maximize spreading within the configuration resulting in an outer shape that subtended 7.80° (height) × 7.80° (width) and an inner shape that subtended 5.38° (height) × 5.38° (width). The first stimulus in every condition had no vertical separation. In Conditions 1 and 2, subsequent stimuli were separated by 0.43° (i.e., the width of the sinusoidal wavelength of the border; this portion was physically removed from the stimulus), 2.44° (i.e., half the width of the original stimulus), and 4.87° (i.e., the total width of the original stimulus) respectively via a central vertical dissection. In Condition 3, Versions B and C were dissected identically to Conditions 1 and 2 except the dissection occurred 1.12° to the right of center. In Version D the left part of the stimulus returned to the center of the screen and the right part was removed entirely.

Design and Procedure. The design and procedure was identical to Experiment 1 and 2 except that participants estimated the magnitude of the left portion of the “doughnut” shape or cross shape.

Experiment 3 Results and Discussion

A 2 (Condition) x 4 (Version) within-subjects ANOVA was conducted to analyze differences in illusion magnitude in the left part of the WCI region for Conditions 1 and 2. Condition 3 used stimuli of different sizes and configurations as well as a different comparison stimulus and was therefore analyzed separately from the first two conditions. In the analysis of Conditions 1 and 2, there was a main effect of Condition as predicted, $F(1,112) = 18.319$, $p < .001$. The removal of the upper and lower stimulus borders in Condition 2 caused weaker illusion magnitudes for all four stimulus versions. Contrary to our hypotheses there was not a main effect of Version, $F(3,112) = 1.198$, $p = .314$ meaning illusion magnitude did not decrease as the horseshoe regions were spread farther apart (see Figure 24). Pairwise comparisons confirmed that no stimulus versions were different from one another in illusion magnitude, $p \geq .098$. The interaction between Condition and Version was not significant. A one-way ANOVA was conducted to analyze the rating data from Condition 3. As with the first two conditions, stimulus version was not a significant factor in illusion magnitude ratings, $F(3,56) = .549$, $p = .651$. Despite having differences in size, configuration, and comparison stimuli, the results were consistent across all three conditions of this experiment.

This similarity was echoed in the handwritten shading data provided by participants as can be seen in the representative heat maps (see Figure 25). Participants did not observe color spreading beyond the unenclosed borders of these stimuli regardless of condition or stimulus version. The fourth stimulus version in Condition 3 (i.e., the cross with the right arm completely absent) was intended to be a stimulus in which color would actually spread beyond the physical borders similar to other unenclosed WCI stimuli (e.g., Figure 4), but no color spreading was reported nor was there a significant reduction in illusion magnitude due to this manipulation. While Condition 2 showed significantly weaker illusion magnitudes than either of the other conditions, $F(2,168) = 22.581$, $p < .001$, the strength of color spreading still did not degrade with disconnection of the halves or increased distance between the halves. This supports our hypothesis that stimulus versions 2 – 4 for all three conditions are being perceptually organized in one of two ways: (1) as two separate "objects" consisting of real borders and illusory color borders or (2) as a single object occluded by an illusory white bar. Pilot data was collected from nine subjects prior to this experiment to determine when these stimuli were organized as one verses two objects. A 3 (Condition) x 4 (Version) within-subjects ANOVA was conducted to analyze this pilot data. There was a significant main effect of Condition, $F(2,96) = 10.419$, $p < .001$, and Version, $F(3,96) = 18.481$, $p < .001$, as well as a significant interaction between the two, $F(6,96) = 4.341$, $p = .001$ (see Table 3). The further apart the two pieces became, the more likely participants were to perceptually organize them as two objects. However, this just meant that the illusory white/orange contour would shift from "belonging" to the occluding white bar when the stimulus was viewed as one shape to "belonging" to the orange WCI stimulus when viewed as two shapes. In Condition 2, participants were much more likely to organize the third and fourth stimulus versions (Figure 22 C & D; i.e., the versions spread the farthest from one another) as two shapes than one. The reduction in fringe in this condition made the phantom occluder organization more difficult resulting in a two shape organization. Interestingly, qualitative pilot data revealed that participants were sometimes able to see some combination of these two organizations. In other words, they saw the stimulus as two separate shapes but could simultaneously see an occluding white bar. The distinction between seeing the stimulus as one shape or two is somewhat irrelevant in terms of color spreading however since color will not spread outside of these “unenclosed” parts under either condition. Color is simply not spreading outside of these parts due to the illusory color contours functionally shifting the WCI stimuli from unenclosed to enclosed. The manipulations used in this experiment demonstrate once again how global context can impact the manifestation of these filling-in processes.

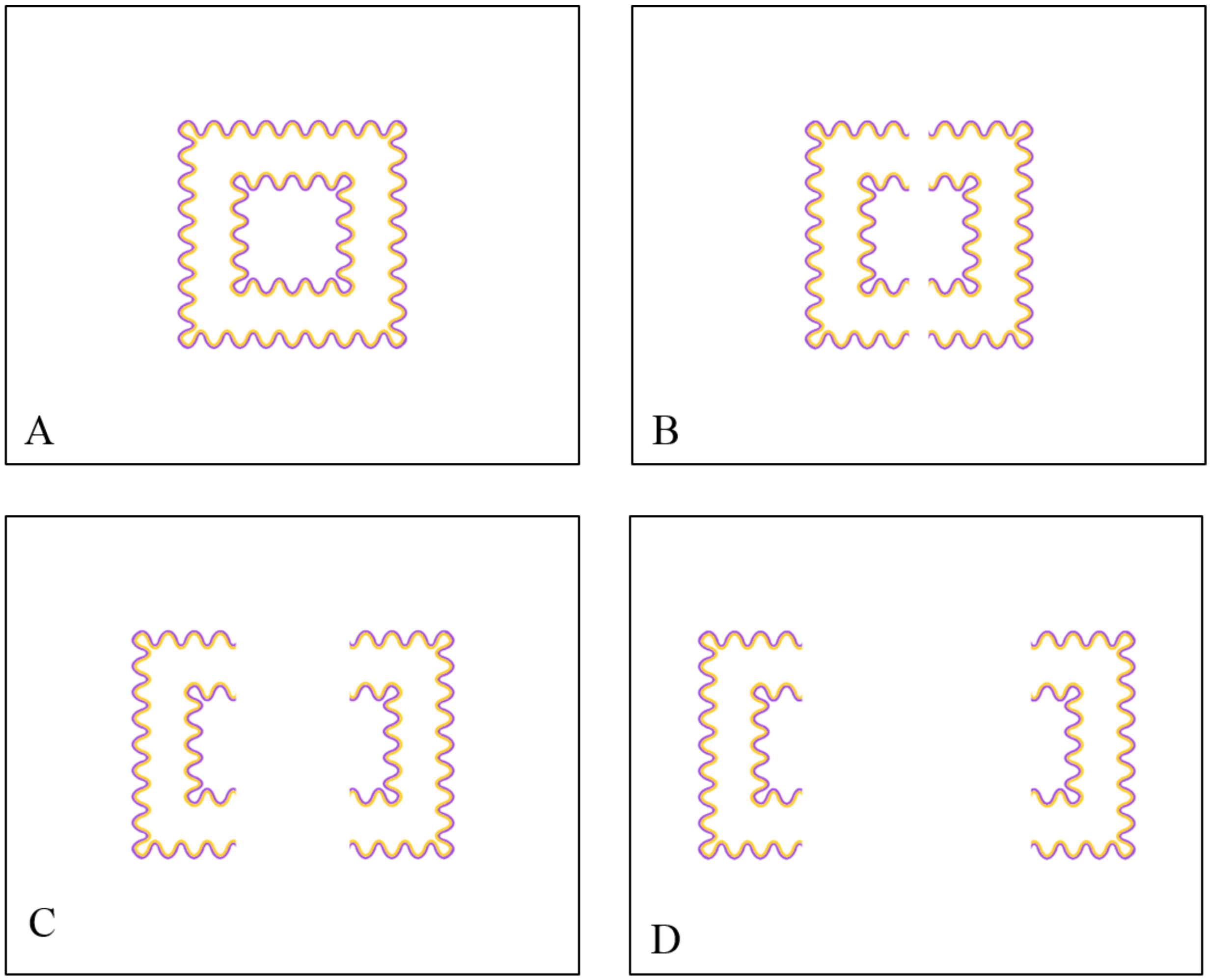

Figure 21. Example stimuli from Experiment 3 Condition 1 consisting of a centrally located wavy orange square with inward fringe and a centrally located smaller square with outward fringe. The central squares are dissected vertically in B which shift apart in C and D.

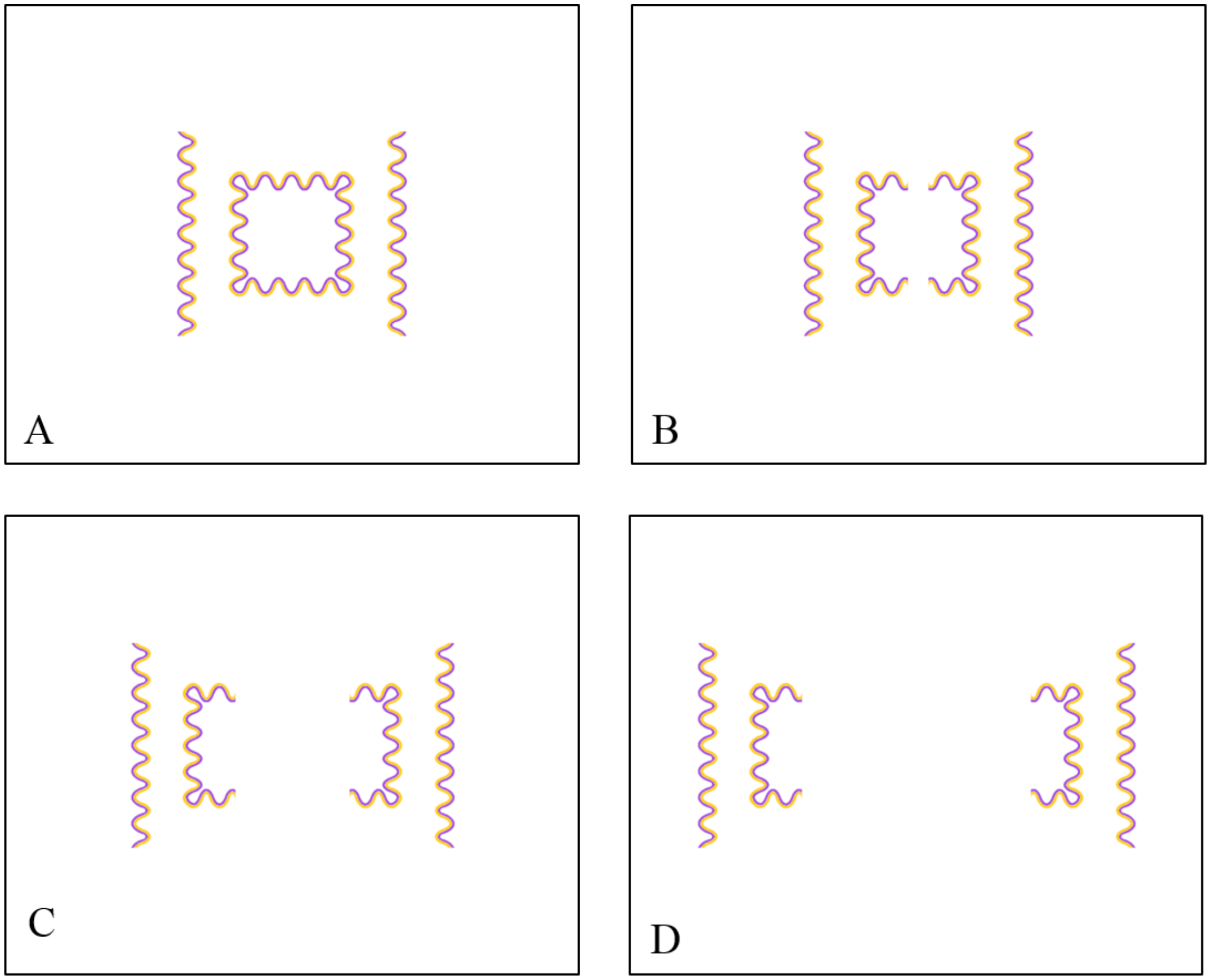

Figure 22. Example stimuli from Experiment 3 Condition 2 consisting of a centrally located wavy orange square without a top or bottom with inward fringe and a centrally located smaller square with outward fringe. The central squares are dissected vertically in B which shift apart in C and D.

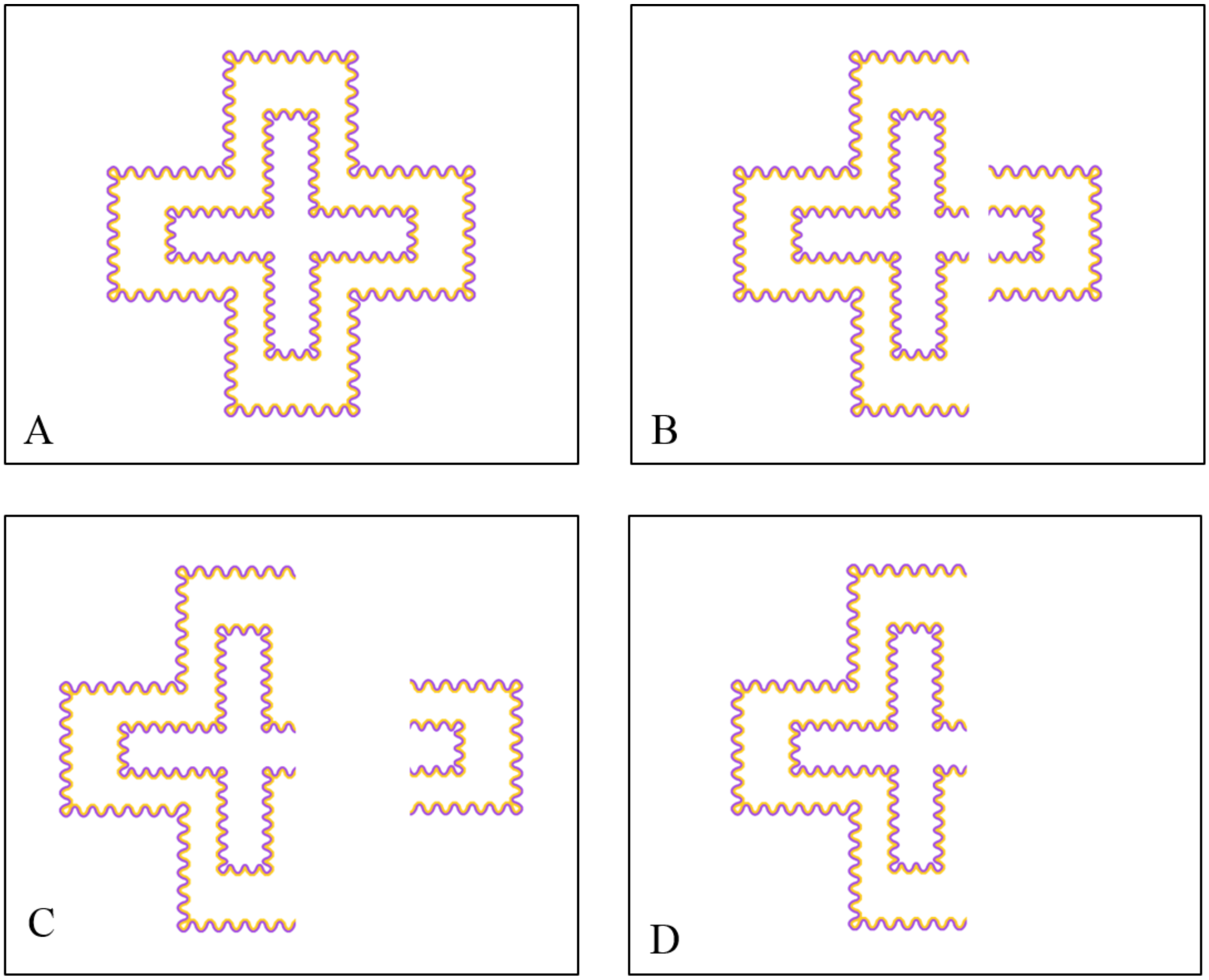

Figure 23. Example stimuli from Experiment 3 Condition 3 consisting of a centrally located orange cross with inward fringe and a centrally located smaller cross with outward fringe. The central crosses are dissected vertically to the right of center in B which shift apart in C. Version D is centrally located with the right region removed.

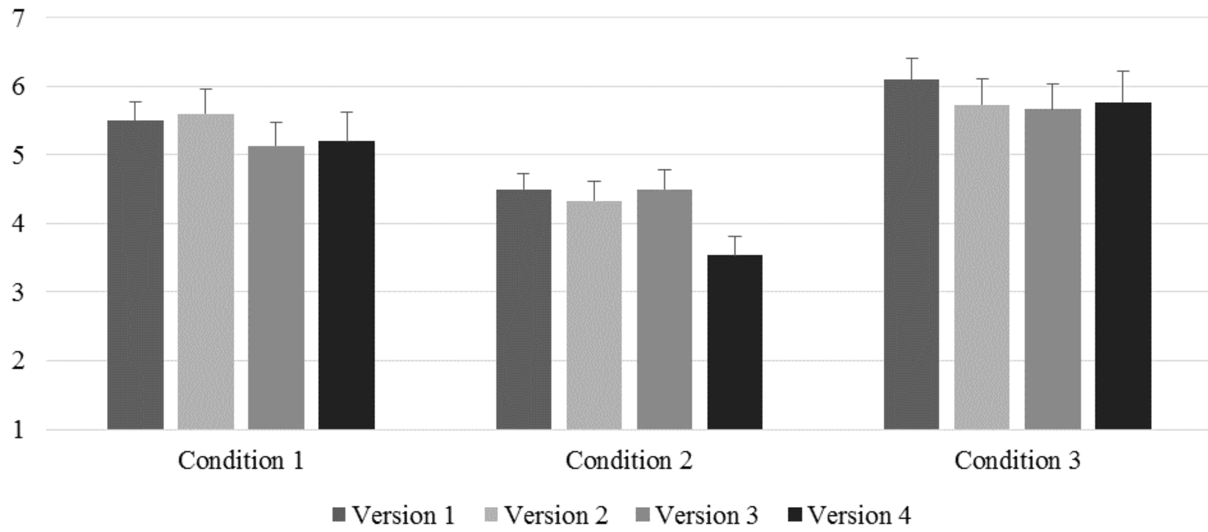

Figure 24. Illusion magnitude data for Experiment 3, Conditions 1 – 3.

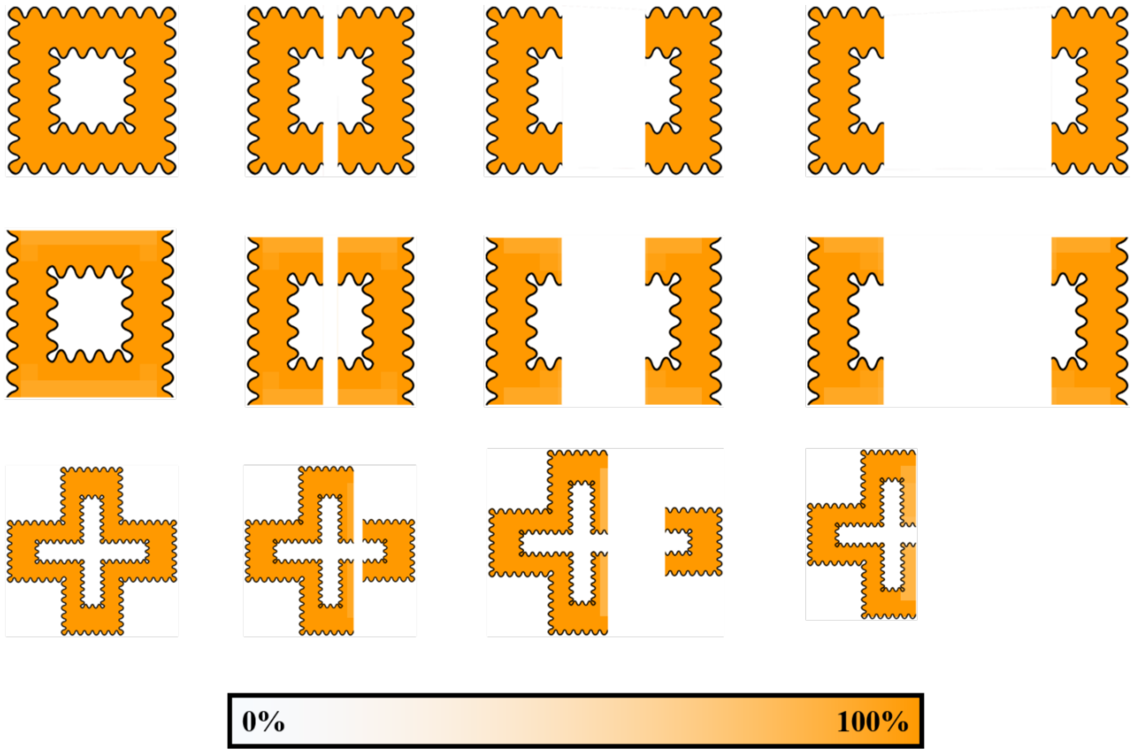

Figure 25. Participants shaded line drawings of the stimuli viewed following each condition. This data was averaged across individuals for each stimulus, and a conditional formatting grid was used to create these heat maps as an approximated visual display of this data. As indicated by the scale below the heat maps, a darker, more saturated orange correlates with a higher percentage of individuals shading this region. These heat maps are not representative of how hard or light someone shaded but rather the percentage of individuals who shaded a particular area. From top to bottom these rows of heat maps are for Conditions 1 – 3, respectively.

Table 3: Experiment 3 Perceptual Organization Pilot Data

	SV1	**SV2**	**SV3**	**SV4**
C1	100*	100	66.7	22.2
C2	100*	88.9	33.3	22.2
C3	100*	100	77.8	100*

Note: Pilot data is from nine subjects reporting whether they perceptually organize the stimulus as one object (e.g., occluded by a white bar) or two distinct objects. The values reported on this table denote the percentage of individuals who saw the stimulus as one object rather than two. The left column represents the condition, and the top row represents the stimulus version. Values followed by an asterisk indicate that only one possible interpretation existed (i.e., the stimulus could only be interpreted as a single object).

CHAPTER 6

GENERAL DISCUSSION

Previous literature investigating the WCI has focused primarily on local and global stimulus parameters affecting the illusion's magnitude and the likely neural mechanisms responsible. In those studies the terms local and global refer to such stimulus parameters as the contrast differences between the fringe and outer contour (local), the reduction of surface area between fringes due to wavy contours (local to global), and how the color spreads across a larger distance into open space or until it meets another fringe (global). Research in color spreading rarely discusses how this phenomenon manifests in stimuli more representative of our three-dimensional world. In the present study the term global refers to the context and configuration of the stimulus beyond the WCI surface itself. By manipulating this global context over three experiments we tested the simple question: Does color always spread outward from unenclosed WCI stimuli? Based on the results of these experiments the answer is clearly 'no'.

In Experiment 1, the WCI was examined by comparing illusion magnitude and where color spreading occurred using a variety of pictures of two- and three-dimensional stimuli. From a contextual standpoint, the local information was now the region containing the color-inducing fringe itself. This local information was largely the same across all conditions of Experiment 1. It was the global configurations these color inducing regions were placed in that were able to affect the illusion. Condition 2 showed that removing the fringe from one part of a two-part two-dimensional shape was sufficient to stop color spreading into that part from the part containing the color-inducing fringe. An illusory color contour is generated separating the part where the fringe is from the part where it is not, indicating the visual system treats these two parts as separate surfaces. This finding is contrary to previous WCI literature which has consistently shown color spreading outward until it reaches a border. The results of this experiment demonstrate that an illusory color border can in some cases be equally effective at stopping color spreading as a physically present border. When the same two-dimensional shapes in Condition 1 became parts of three-dimensional shapes in Condition 3 there was an unexpected drop in illusion magnitude. Despite the color spreading regions being identical in both of these conditions, the additional surrounding contours in the stimuli in Condition 3 negatively impacted the strength of the WCI illusion highlighting how easily color spreading illusions are affected by context. Similar to Condition 3 incorporating Condition 1 stimuli into a three-dimensional context, Condition 4 incorporated the same two-part two-dimensional shapes from Condition 2 into a three-dimensional context. Unlike the Condition 1 vs 3 comparison where illusion magnitude was reduced, the lower magnitude in Condition 2 resulted in no difference in magnitude with Condition 4. The shape in Condition 2 was phenomenally divided into two parts, therefore, the implied three-dimensionality imparted by Condition 4 was not a necessary contextual factor in organizing this “unenclosed” space into two distinct parts as initially predicted.

Experiment 2 used nearly identical configurations from Experiment 1 except they depicted wireframe surfaces and objects rather than solid ones. The color spreading regions in this experiment more closely resembled NCS than WCI stimuli due to the fact there were now contours within the region where the color spreading occurred. Condition 1 produced the same illusion magnitude in Experiment 1 and 2 allowing direct comparisons of any differences between experiments. In Experiment 2, illusion magnitude in Conditions 2 – 7 was significantly lower than Condition 1 due to a combination of factors including the addition of contours inside the color spreading region (i.e., Conditions 2 – 7), transparency (i.e., Conditions 2 – 7), missing borders (i.e., Conditions 3 and 5), and reduced fringe (i.e., Conditions 6 and 7). Despite these differences, illusion magnitude across the two experiments was not statistically different. As in Experiment 1, participants did not observe color spreading beyond the end points of the fringe in any partial fringe condition (i.e., Conditions 3, 5, 6, and 7) as confirmed by illusion magnitude ratings and handwritten shading. Instead, participants perceptually organized the WCI surface in all of these conditions into two separate abutting parts of a surface on the same plane. If these were objects in the real world, they would be wire frame objects with a transparent orange film across one portion of the front surface with either a clear film or no film covering the remainder of this surface. The illusory color border perceived belongs to the WCI surface rather than the "adjacent" non-colored "surface" since the two regions seem to be processed as if they are completely separate.

Experiment 3 examined how pictures of more traditional two-dimensional WCI stimuli are perceived when disassembled into multiple parts. Through various dissections and manipulations we were able to see how simple global stimulus changes impact color spreading as well as test previous notions pertaining to how the WCI will spread in the absence of a physical border. Once split, these WCI stimulus parts were no longer physically enclosed. The fact color failed to spread outside of these now physically open configurations further confirms that global configuration is an important factor in how color spreading manifests. The lack of color spreading in this experiment is also notably different from the first two experiments since stimuli from Experiment 3 were truly unenclosed. In Experiments 1 and 2 there was a reduction in fringe which meant it may have been possible for color to spread into a portion of a surface or an adjacent part/side of a shape/object which did not contain fringe. In Experiment 3 the stimuli were literally divided into two physically separate parts. In so doing, unenclosed WCI stimuli were created that were more similar to traditional unenclosed WCI stimuli (e.g., Figure 4) than to the stimuli in Experiments 1 and 2. The final stimulus in Experiment 3 was a three-armed cross that was completely open on the right side. Contrary to our expectations, color still failed to spread beyond the outer contours defining the cross. Just as in the first two experiments, an illusory color contour belonging to the WCI stimulus abruptly stopped and contained the color spreading. Another interesting factor in this experiment was the phantom occlusion experience reported in several of the stimulus versions in all three conditions. The WCI has a strong figural nature which tends to cause any WCI surface to be perceptually organized as the foremost surface. In this experiment, an illusory white bar was often perceived to be occluding either an amodally completed unified WCI surface underneath or between two WCI surfaces separated by some distance. This is one of the first examples we are aware of where a WCI surface is not perceived as the foremost surface in a stimulus. Interestingly, this organization forces one illusion (i.e., the phantom occluding bar) to interact with a second illusion (i.e., the WCI surface or surfaces). Despite the areas inside the WCI "doughnut" and the occluding bar being physically identical to the white background, the occluding bar appears to be brighter or "whiter" than the background while the WCI region appears to be a colored surface. These three differing and simultaneous perceptions of physically identical white space are visual evidence of perceptual organization and figure-ground mechanisms at work. While it is possible these illusions are simply byproducts of normal visual processing, it is likely the phenomenological experiences reported in these experiments are indicative of underlying mechanisms and processes normally implemented by the visual system to organize and fill-in surfaces and objects and visually separate them from the background.

The FAÇADE and LAMINART theories (Grossberg, 1997, 1999; Grossberg & Yazdanbakhsh, 2005; Raizada & Grossberg, 2003) can be used to explain the WCI – including our new findings related to the WCI in context. The figural component of these theories is related to form processing, color spreading is related to surface processing, and the depth component is related to the organization of the WCI surface as figure in front of a ground (Bertamini, 2006; Pinna & Tanca, 2008; Zweig et al., 2015). Grossberg (1997, 2016) and colleagues (Grossberg & Mingolla, 1985) define the mechanisms underlying these processes as the BCS and FCS, respectively. We know an unenclosed WCI stimulus will spread the perception of color indefinitely beyond its border (see Figure 4). However, a real surface does not leak its color into space due to end-cuts created by the BCS that stop the color from leaking (Grossberg, 2014). These end-cuts can be used to potentially explain the lack of color spreading past the end points of the fringe in all three experiments. Based on this model, the BCS generates end-cuts signaling the end of a border thus functionally dividing a physical shape into two parts. The FCS involved with the filling in of color would be responsible for spreading color into the part with the fringe while not generating color spreading in the other part. The implied three-dimensionality in the conditions in Experiments 1 and 2 did not impact our results as much as expected. Future research using real three-dimensional objects and surfaces rather than computer-generated pictures may be needed to better examine the impact of three-dimensionality on color spreading.

The results of the present study are also relevant to the color filling-in and symbolic color representation theories which model the color filling-in that occurs with physical surfaces and objects in the real world (von der Heydt et al., 2003; see Figure 5B & 5C). Using the example from Figure 5, we can see how the color filling-in theory allows for a lateral sharing and processing of wavelength information between RFs at the circle's border. These signals are kept strong due to the combination of horizontal connections and high contrast between the orange circle and gray surrounding surface. The symbolic color representation and color filling-in theories are similar in their emphasis of border signals as being important for perception of the orange circle. In the color filling-in theory however, the form of the circle is also involved. Border-selective RFs integrate at a higher level to generate a neural signal signifying the presence of an orange circle. Thus, in this model, the global configuration of the visual stimulus is ultimately generating the perception. Both theories relate to processing of wavelength stimulation, but both models would also be applicable to the filling-in of color experienced in blind spots, scotomas, and after stimulus adaptation. In fact, it would be advantageous for our visual system to implement a process like the ones proposed in these theories for all surface color processing due to the benefits of increased processing speed and better integration of visual stimuli across the visual field. These filling-in theories could also provide plausible explanations for the different types of illusory color observed in color spreading illusions. The perceptual filling-in of color in illusory color spreading – including the nature of spreading observed in our experiments – is likely to be similar to the other forms of color filling-in described above in terms of processing and purpose. While it is possible illusory color spreading is simply a byproduct of normal physiological processing of retinal information, it is likely these illusions are visual evidence of a ubiquitous color filling-in process that is constantly functioning and interacting within the global context of our visual field.

Overall, the present experiments explored how global stimulus context can impact color spreading illusions like the WCI. These illusions are likely a byproduct of a useful heuristic in the visual system being exposed considering color spreading is not so easily noticed in our normal human visual experience. “Shortcuts” are taken by our visual system to sharpen, enhance, and speed up processing of retinal information working in conjunction with prior knowledge and experiences to generate the rich seamless perceptions we experience. This is why it is important to study these illusions and the mechanisms responsible for them in ways more representative of our three-dimensional world. In doing so we will gain a better understanding of how these mechanisms and models may actually operate within the visual system. The three experiments reported here are some of the first to explore how color spreading can be influenced by stimulus conditions containing shape and three-dimensional information more typical of our visual experience.

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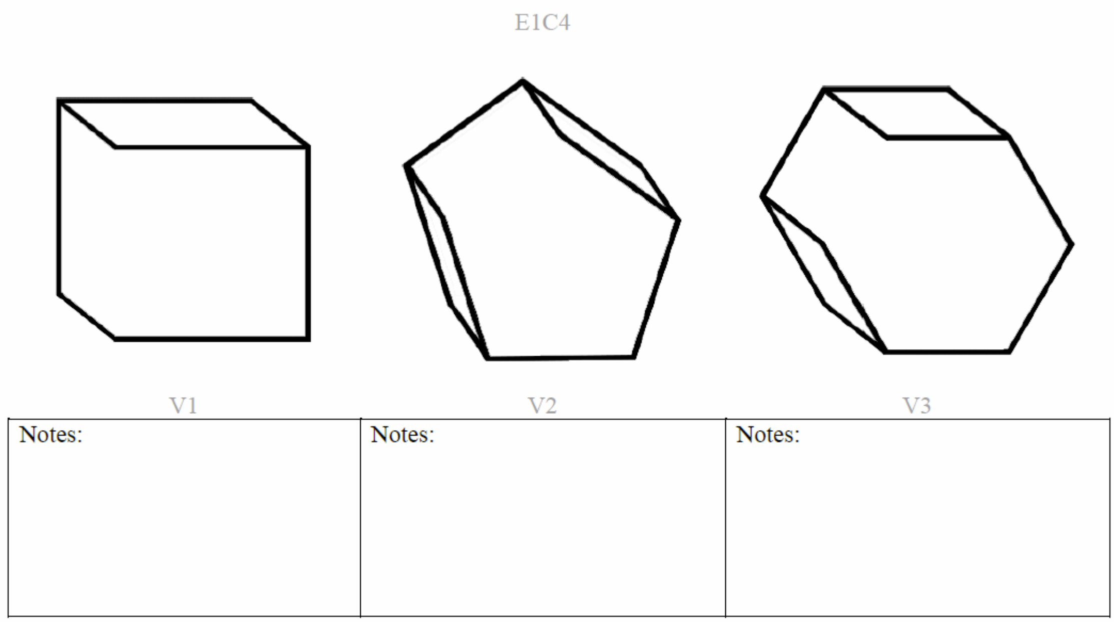
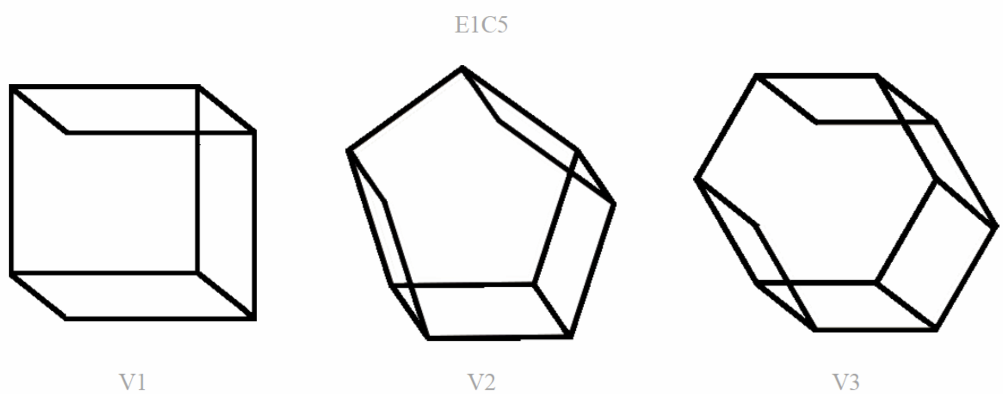
Appendix A.1

Example of Handwritten Measure Card from Experiment 1 (Condition 4 shown)



Appendix A.2

Example of Handwritten Measure Card from Experiment 2 (Condition 5 shown)



Notes:	Notes:	Notes:

Appendix A.3

Example of Handwritten Measure Card from Experiment 3 (Condition 2 shown)