University of Nevada, Reno

Understanding Misperceived Size through Assimilation in a Novel Illusion:
The Binding Ring

A thesis submitted in partial fulfillment
of the requirements for the degree of

Bachelor of Science in Neuroscience and the Honors Program

by

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Abstract:

How do we perceive the size of objects? This research attempts answer a small part of that question by describing and quantifying the binding ring illusion, a novel (and previously uncharacterized) illusion of misperceived size. Following the establishment of the binding ring as a legitimate size illusion, experiments were performed in an attempt to identify what visual processing stream mechanisms were responsible for the illusion and further, to obtain any information as to the relative whereabouts of said mechanism(s) in the visual processing stream. These experiments were performed because many processing mechanisms of the visual stream (and their relative location therein), especially those in the relatively 'high' portion of the visual stream, are very poorly understood. The results of the study gave three primary results: first, the binding ring illusion occurs primarily through a process of assimilation; second, this assimilation process is heavily influenced by a process of perceptual unification; and third, the mechanisms of assimilation and unification are likely located relatively high in the visual processing stream, very likely occurring after spatial frequency integration and either after or during the creation of global shape representations.

Acknowledgements:

First and foremost I want to thank Dr. Gideon P. Caplovitz for his direction throughout the entire process – I would not have accomplished this degree of quality with any other advisor. Since the day I joined the C-lab Dr. Caplovitz has been constantly challenging me to reach my potential while simultaneously preparing me for a successful career, academic or otherwise. I could not have asked for a better mentor.

Additionally, I would like to thank J. Daniel McCarthy (from the C-lab), as he was always willing to help me with any aspect of the project (especially the statistics & figures) and pick up the slack when I needed help.

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Introduction:

Visual illusions play a role in psychophysical investigations as understanding the underlying causes of a perceptual illusion can reveal how the brain processes visual information (Walsh & Kulikowski, 1998). When compared to other neural systems, the visual system is one of the most well understood and well documented sections of the brain; that being said, even in the well documented systems, there is still much to be learned.

Classic size illusions, such as the Müller-Lyer, Ebbinghaus and Delbouef illusions (figure 1 below), have helped to reveal various aspects of the visual system (Müller-Lyer 1889; Delbouef 1893; Ebbinghaus 1902). And as visual perception occurs through an unconscious, constructive process, visual illusions provide a useful tool in investigations – they give researchers 'errors' or 'artifacts' of the visual stream process which can be characterized and (relatively) located within the visual processing stream.

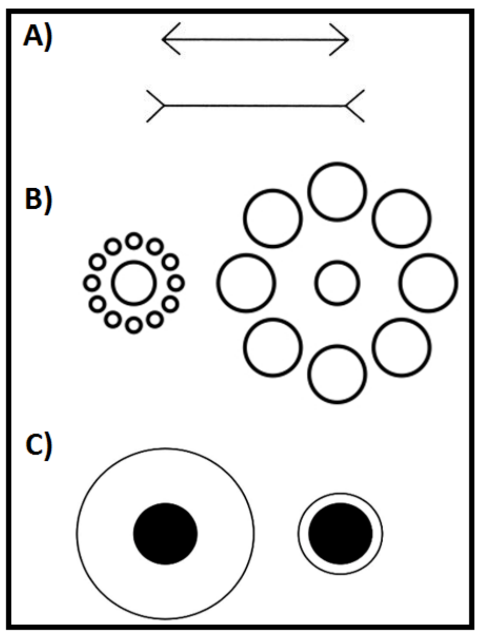

Figure 1. Classic size illusions. **A)** Müller-Lyer Illusion (Müller-Lyer 1889) **B)** Ebbinghaus Illusion (Ebbinghaus 1902), **C)** Delbouef Illusion (Delboeuf 1893)

A previously unknown visual processing error (or artifact) was discovered by Dr. Gideon Caplovitz, a professor of psychology at the University of Nevada, Reno; he named it the binding bing illusion (McCarthy, Kupitz and Caplovitz, 2011). Figure 2 (below) presents an example of the binding ring illusion, which arises when two identical circular arrays of small circular elements are placed in proximity, and one of them is superimposed with an intersecting larger circle, henceforth referred to as the "binding ring."

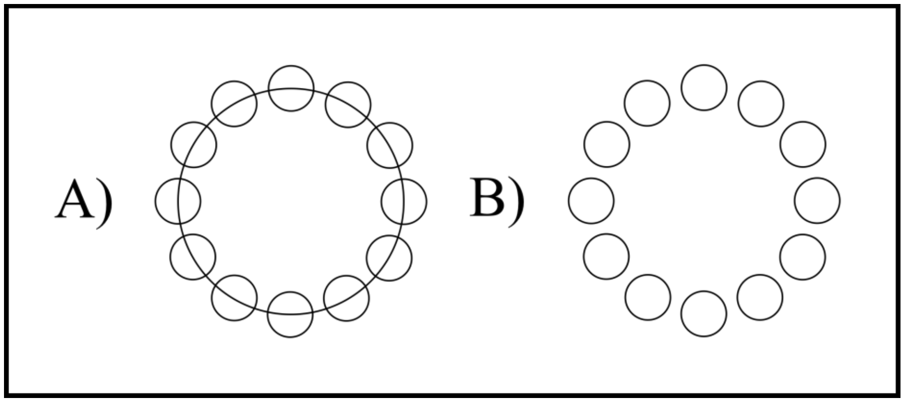

Figure 2. Demonstration of the "Binding Ring" and its illusory effect. When participants view these two stimuli, the overall size of the array of elements with the superimposed binding ring (A) is perceived to be smaller than the unbound array (B), despite the arrays being identical.

The binding ring illusion could be viewed as variants of the Ebbinghaus or Delbouef illusions; however, the specific configurations investigated here (especially the overlap of the ring and array) have not previously been characterized. As such, this study first characterizes the illusory effect caused by the binding ring, and then reveals the mechanisms of and their locations in the visual processing stream.

The first experiment (E1) measures (and thereby proves) the illusory effect seen in the binding ring. Follow-up experiments then investigate: (E2) the importance of the binding ring size, (E3) the role and effect of different spatial frequency domains in the illusion, (E4) alterations in array component size, and finally (E5) local form configural alterations.

Because of the nature of the binding ring illusion, and illusions in general, this investigation attempts to increase the understanding of size perception and the visual processing stream, through the exploitation of inborn errors and artifacts of perception – illusions.

Literature Review:

Both size perception and visual illusions have a robust history predating experimental psychology. A convenient organization of the history of perception is provided by Walsh and Kulikowski (1998), wherein the researchers divided perceptual history into three primary phases. Certain gifted individuals were ahead of their respective phases: for example, Ptolemy (90-168 CE) accurately understood some basic principles of optics (the behavior and properties of light), and Alhazen (965-1040 CE) helped to formulate the beginnings of both physiological optics and size constancy (Walsh and Kulikowski 1998; Wade, 1998). However, the rare perceptual visionary is ignored to create a general flow of visual perception history, which is as follows.

Phase one consists of the time preceding the fully realized theory of optics. The general view of phase one was that stimuli directly imprinted perceptual knowledge onto the senses. Phase two began after the eye's optical functions were understood. Descartes (1637) and Berkeley(1709) first investigated the main problem of phase two: determining how sensory information leads to perception. Most researchers of phase two correctly believed that perceptual knowledge resulted from cognitive processing of stimulus information, but incorrectly assumed that stimulus information was sufficient to explain the entirety of perception (Walsh and Kulikowski 1998; Wade 1998). Finally, the third and current phase began when Hermann von Helmholtz (1867-1962) proposed that perception was a hypothetical construct created by cognitive processes based on insufficient stimulus information; Helmholtz was the first scientist to propose that perception is generated through unconscious cognitive inferences. (Helmholtz 1867/1962, cited by Walsh & Kulikowski, 1998).

During Helmholtz' lifetime, two particular theories of psychology came into favor – behavioral psychology (behaviorism) in the United States, and Gestalt psychology (gestaltism) in Germany (and eventually spreading throughout Europe) (Mandler, 2007, p. 97-102). Gestaltism is relevant to the research herein, whereas behaviorism is not – as such, only gestaltism will be discussed. In German, the word “gestalt” can be taken to have two meanings: it has the connotation of “shape” or form” as a property of things, but also that an entity can have individual and concrete characteristics, one of which being that it exists as something ‘detached’, having shape or form as one of its attributes (Köhler, 1929, p. 187-189). The underlying idea of gestalt theory is that the brain is holistic; the properties of the brain (and especially perception) cannot be entirely explained by its component parts. The overall properties of Gestalt perception are emergence, reification, multistability, and invariance (Lehar, 2004).

The idea of *gestaltqualitäten* (loosely: whole-form qualities) was first introduced by Christian von Ehrenfels of the University of Berlin, who noted that sensory fields had qualities that could not be entirely explained on the basis of “sensations” [perceptual stimuli] alone (Köhler, 1929, 187-193). Gestaltism quickly spread through the University of Berlin, and was continually advanced by German psychologists there - especially Wolfgang Köhler (“the whole is *different* [not greater, a prevalent misquote] than the sum of the parts”), Max Wertheimer (gestalt properties are derived from top-down processes), and Kurt Koffka (gestaltism is not exclusive to perceptual psychology), some of the most recognized students of Carl Stumpf (King and Wertheimer, 2005, p. 123, p. 154; Peterman, 1932, p. 32).

Sometimes referred to as the triumvirate of Gestalt Psychology, the three aforementioned men responsible for the proliferation of gestaltism were further integral in its ‘immigration’ from Germany to the United States. Koffka immigrated in 1925, Wertheimer in 1933, and Köhler in 1935; fortuitous events given the destruction of German psychological culture during the rise of Nazi Germany and WWII (Mandler, 2007, p. 139-164). The movement of gestaltism from Germany to the United States started the integration of information-processing and cognitive-constructivist theories into the development of more modern psychological theories. Like many of the earlier theories, gestaltism is no longer considered to be a major school of thought in psychology, primarily because of said integration into more current and refined psychological theories developed in America (Mandler, 2007, p. 164-167). But despite the decline of gestaltism, American psychology was changed in a widespread and lasting manner with its integration, as it helped to spark the "cognitive revolution" (Mandler, 2007, p. 164-167).

Unsurprisingly, this cognitive revolution was approached in a multitude of ways – one of which was through experimentation with illusions. The aforementioned Müller-Lyer (1889), Ebbinghaus (1902), and Delbouef (1893) illusions (figure 2, above), had been presented prior to the cognitive revolution - but had not been completely explained. Under the view of gestaltism, illusions are essentially artifacts in perception due to visual processing mechanisms – meaning they have the potential to reveal said mechanisms and their relation to perception. New or uncharacterized illusions can be especially important in the advancement of psychology and neuroscience; for example, Hermann's grid illusion (figure 3A, below) helped lead to the development of the idea of receptor fields (Hermann, 1870; Spillmann, 1994). Similarly, the Ponzo illusion (figure 3B, below) is often interpreted as occurring because of the percept of perspective (Ponzo, 1912), which is likely correct as results analogous to those predicted by a perspective interpretation were observed in an experiment involving sensory substitution using an auditory presentation paradigm (Reiner & De Volder, 2005).

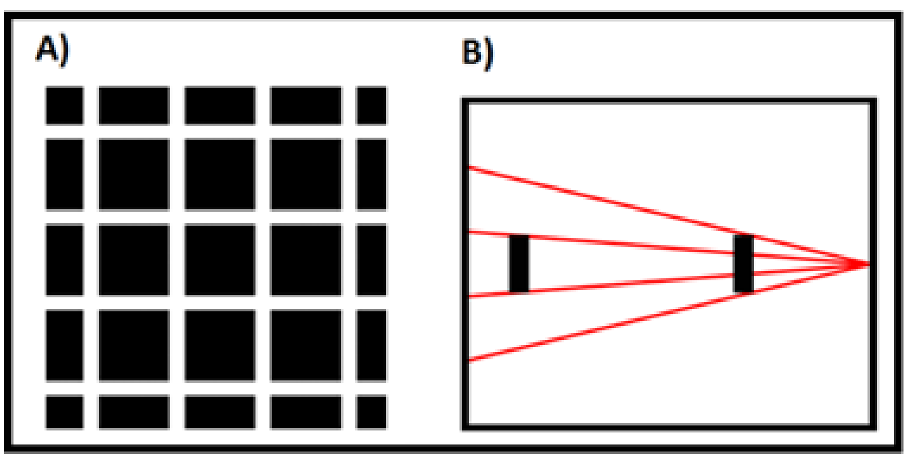

Figure 3. Experimentally valuable illusions. Illusions such as these have helped scientists understand various portions of the visual system of the brain. A) The Hermann Grid Illusion (Hermann, 1870) B) The Ponzo Illusion (Ponzo, 1912)

Many of the aforementioned illusions fall under the broad category of illusions of contrast and assimilation. Illusions of assimilation or contrast are based on the configuration of the visual stimulus, with the perceived size of individual components being distorted in a manner dependent on the context in which they are embedded (Girgus and Coren, 1982). Generally, when the component of interest is distorted towards the surrounding context it is considered to be an effect of assimilation, whereas when the direction of distortion is away from the surrounding context it is an effect of contrast (Girgus and Coren, 1982). Initial theories on assimilation and contrast proposed that their illusory effects shared a common cognitive mechanism; however, recent studies have shown that the two effects in fact compete antagonistically with each other, a finding which implies assimilation and contrast have their own unique processing mechanisms in the visual stream (Goto *et al.*, 2005; 2007). Further, the same studies determined that illusions of assimilation and contrast were derived from size-judgment processes (Goto *et al.*, 2005; 2007).

Illusion based experimentation has certainly contributed to the understanding of the visual system; however, many experiments without the use of illusions that have led to conventionally accepted standards in the field of visual processing; one of the most integral parts of current understanding of visual perception is referred to as size constancy (Gruber, 1954). Simply put, size constancy means that an object will appear to be the same size despite alterations in depth, and therefore alterations on the visual angle of the object (figure 4, below).

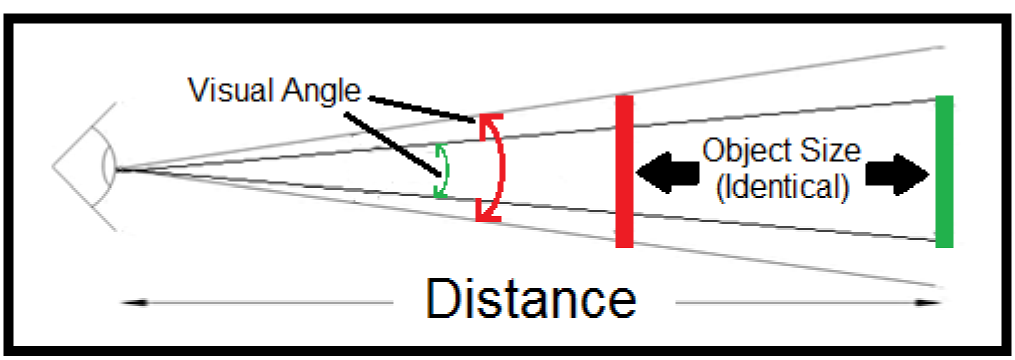

Figure 4. An illustration of size constancy. An object will be perceived as remaining the same size at different distances despite altered visual angle.

While size constancy remains a cornerstone of cognitive visual processing theories, it is imperfect; for example, objects projected onto mirrors or windows are overestimated in size (Lawson *et al.* 2007). Furthermore, one study illustrates the constructive and therefore error susceptible nature of size constancy: the accuracy of size constancy judgments is directly proportional to the amount of visual information available (Kubzansky *et al.*, 1971**)**. Consistent with the early ideas of gestaltism, these findings are indicative of an unconscious, top-down, and constructive paradigm of visual information processing.

This top-down processing of visual information is well accepted in current models of visual processing. Another example of the top-down organization of the visual stream is the processing order of spatial frequency information (figure 5, below). One experiment posits that low spatial frequency information is processed more quickly than high spatial frequency information, while high spatial frequency information provides a more accurate account of the overall scene (Brown & Weisstein, 1988). Further, the same study showed that relative amounts of high and low spatial frequency often leads to the perception of relative depth, despite a lack of stereoscopic depth cues – that is, seeing depth when in truth there is none (Brown & Weisstein, 1988). Interestingly, certain illusions, such as the aforementioned Müller-Lyer illusion (figure 1A, above) are only present with the inclusion of low spatial frequency information (Coren et al, 1976), implying that spatial frequency domains play an integral role in some illusory percepts.

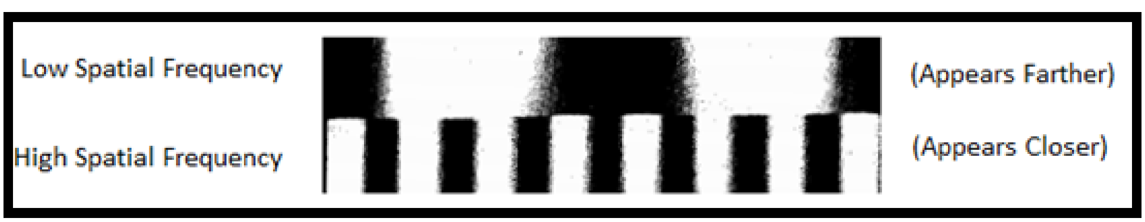

Figure 5. A demonstration of spatial frequency. The more changes there are per degree of visual angle, the higher the spatial frequency is.

Despite the numerous advances in perceptual psychology, the literature shows that a rather large portion of the visual stream – and the cognitive processes therein – remain unknown.

Visual perception started as the idea that stimuli ‘imprint’ themselves onto the senses (phase 1), an idea eventually disproved with the advent of optics. Advances in optics further lead to refined theories of visual perception, which posited the perfect processing of stimuli (phase 2). Helmholtz then further revised the theories of phase 2 upon his discovery that visual perception is subject to unconscious cognitive processing, an idea marking the beginning of the third and current phase in the history of visual perception. Since Helmholtz’ realization that perception arises through unconscious and constructive processes, psychologists (and recently neuroscientists) have strived to understand these mechanisms of perception – continually creating and refining theories in the process, and generating ideas such as gestaltism. Thus, the research herein is conducted with the goal of contributing to the ever evolving theories of perception and visual processing through the characterization of a novel illusion: the binding ring. The characterization of the binding ring is achieved through psychophysical methods, which remain useful and (importantly) non-invasive tools for research in neuroscience.

Methodology: Participants

There were no expected risks to the participants past those of regular computer usage, and as such these experiments were cleared with the UNR Institutional Review Board. All participants reported normal or corrected-to-normal vision. Total participants in each experiment were n = 5, 10, 12, 6, 5 for experiments 1 through 5 respectively. All participants were naïve, meaning they had no prior knowledge of the expected outcome, and further, no participant took part in more than one experiment. Participants received course credit for their participation. Prior to participating, each observer provided informed consent according to the guidelines of the Department of Psychology and the IRB of the University of Nevada Reno.

Methodology: Apparatus and Display

This research was conducted using stimulus presentation programs created in MATLAB (Mathworks Inc., Natick, MA), and presented using the Psychophysics Toolbox (Brainard, 1997) I was the primary programmer, with contributions and input from Dr. Gideon Caplovitz and J. Daniel McCarthy (2011), both of whom also assisted with statistical analyses and figure creation. The stimulus computer was a 2.4 GHz Mac Mini with an NVIDIA GeForce 320M graphics processor (256MB of DDR3 SDRAM), and the stimulus monitor was a Dell Trinitron P991 monitor (19 inches, 1024 × 768) with an 85 Hz refresh rate. Participants were placed 57.3cm away from the monitor (ensuring one cm on the monitor = one degree of visual angle), and then presented stimuli and asked to report their percepts.

Experiment 1: Quantification - Methods

Participants (n=5) were first presented with a small fixation point of 0.35° of visual angle (VA) in the center of the screen for 500ms, and then presented with two circular arrays (a reference and a test or control array) and asked to report which array was larger by pressing one of two buttons – a 2 alternative forced choice (2AFC). The same reference, an unbound circular array of smaller circles (of diameter 0.5° VA) fixed at a radius of 3° VA (figure 1B) was presented in every trial, along with either a test(bound, figure 1A) or a control(unbound) array. In the test condition, the radius of the binding ring matched that of the radius of the array (as measured from the array center to the center of any component circle). The unbound array was utilized to ensure that the participants could accurately report their percepts; further, the psychometric curve generated from these data provides a point of comparison in later analysis. The method of constant stimuli was used, with the test stimulus having a radius selected from a list including 2.5°, 2.625°, 2.75°, 2.875°, 3.0°, 3.125°, 3.25°, 3.375° and 3.5°. The side on which the reference array was presented was randomly determined on each trial, with the test or control array then appearing in the other possible location. In total there were 18 trial types: nine possible radii for both the test(bound) and control(unbound) array types. Trials were pseudorandomly ordered so that 20 of each trial type were presented for a total of 360 trials. An illustration of one stimulus presentation is shown on figure 6.

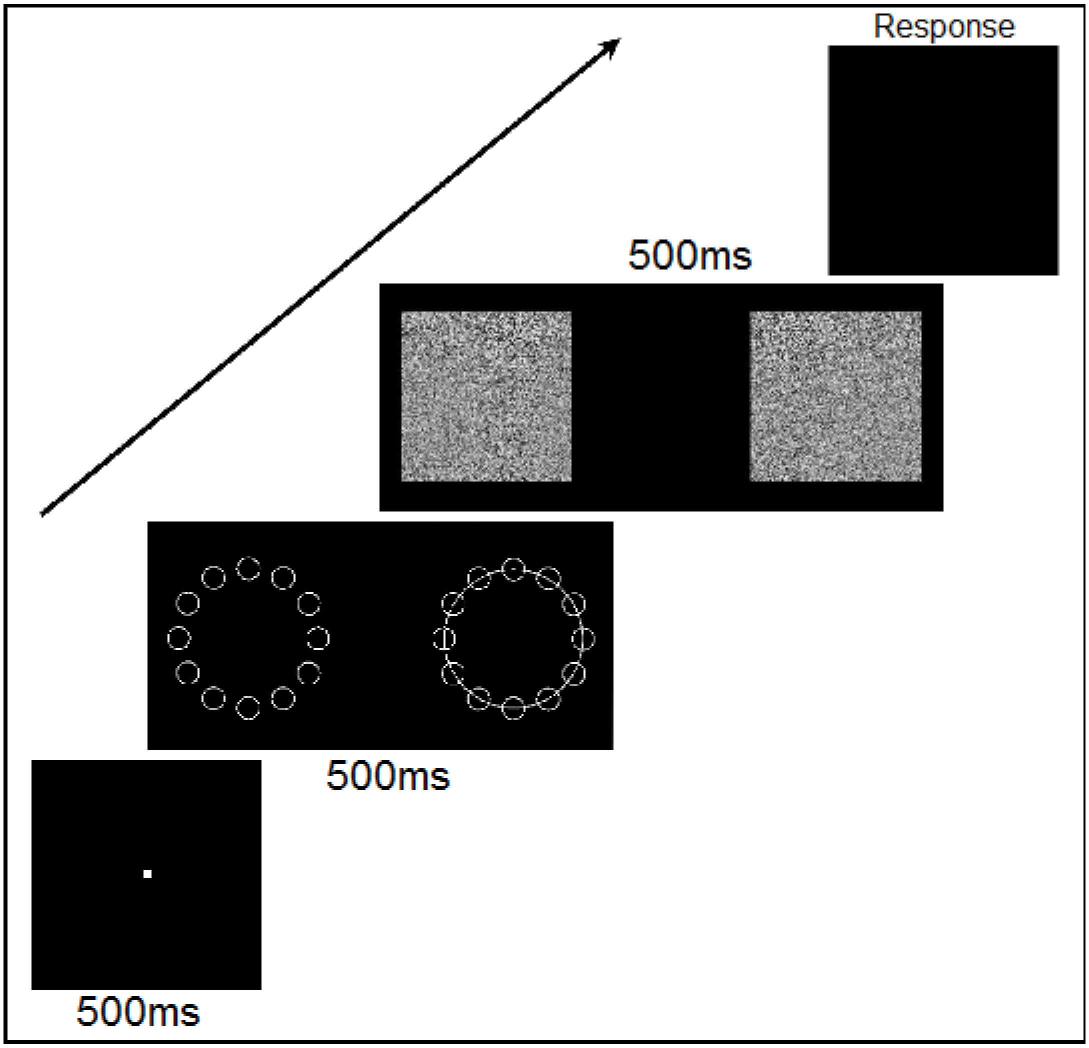

Figure 6. Stimulus presentation paradigm. Participants were shown a central fixation point for 500ms, two stimuli (reference and test or control) for 500ms, random noise for 500ms, and then prompted for a response.

To prevent observers from basing their relative size judgments on horizontal matching or distance comparisons with the edges of the monitor, on each trial the center of each array was randomly positioned within a circular radius of 1.16° VA centered 6.75° VA to the left or right of the central fixation point. Participants were instructed to maintain fixation on the center of the screen throughout the experiment. Prior to the experiment, participants were trained on 20 trials that were not included in the analyses.

<u>Experiment 1: Quantification - Results</u>

The percentage of times the test or control array was perceived to be larger than the reference was calculated for both array types and all possible radii. Thus, for the test (bound) and control (unbound) arrays, nine values (one for each radius) were calculated. A sigmoidal-shaped function was then fit to the corresponding data for each of the two test arrays using MATLAB and the following equation: $f(x) = 100 \times \left[\frac{e^{b_1 + xb_2}}{1 + e^{b_1 + xb_2}} \right]$; this equation was used as it is one method for analyzing the psychophysical data obtained through the method of constant stimuli (Gescheider 1997). The resulting curves plotted for the mean responses across participants are shown in Figure 7(below).

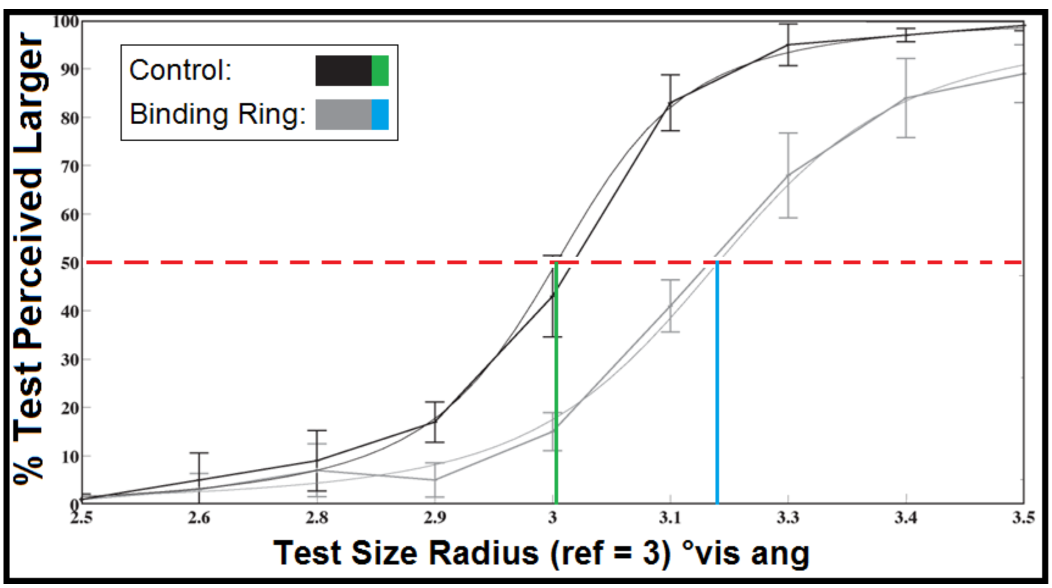

Figure 7. <u>Mean data and generated curves of experiment 1.</u> Psychometric curves generated from the mean fit of the data averaged across all participants. The mean PSEs (figure 8, below) for the test and control stimuli conditions were determined by extrapolating the location in which the generated curve was at chance (50% - red dashed line). Error bars represent standard error of the mean.

The clear and steep-sloped sigmoidal shaped psychometric curve derived from the control condition (both stimuli unbound) confirms that participants were able to perform the task and accurately report their percept. The participants' accuracy on the task was further verified by the fact that participants were at chance performance when the two arrays were indeed the same size. The second psychometric curve derived from the test (bound) condition demonstrates that binding an array results in the underestimation of its size. The points of subjective equality (PSE: the size at which the test array is perceived as equal in size to the reference) were determined for each subject by interpolating the 50% chance level from the function fit to the data ($x = -b_1/b_2$). The 50% chance level was used because it signifies the point at which the participant was 'at chance' – the participants were effectively guessing which stimulus was larger, implying they are being perceived as equivalent in size. Figure 8 (below) illustrates the mean point of subjective equality across subjects for the test and control arrays.

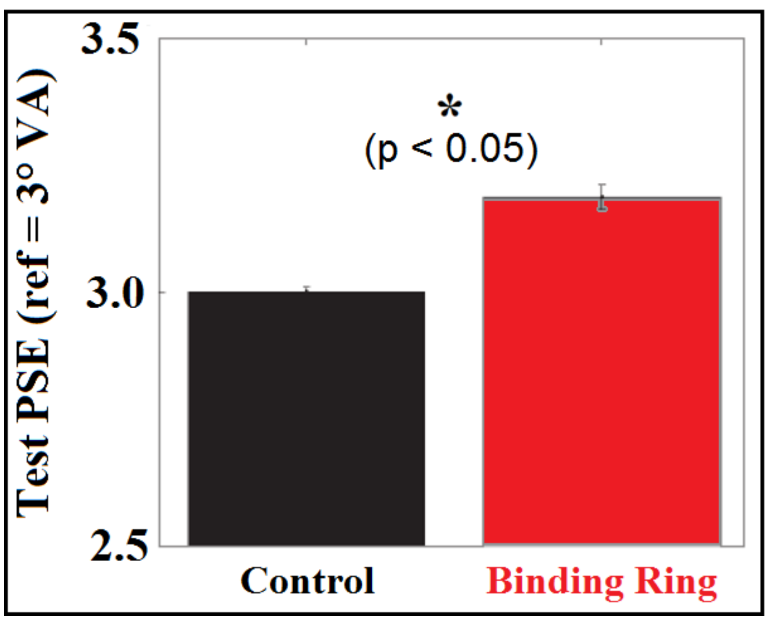

Figure 8. Point of Subjective Equality (PSE) for control and binding ring conditions. The mean PSEs for the test and control stimuli arrays were determined by interpolating the location where the generated curve was at chance (figure 7, previous page). The control PSE (~3.0) indicates participants could accurately judge the radius of an unbound array. The binding ring PSE indicates that the size of a bound array must increase by ~0.16° to be perceived as equal in size to an unbound array.

A paired t-test between the mean PSEs of the test and control arrays revealed that the addition of the binding ring significantly ($t(4) = 7.71$, $p < .01$) reduced the perceived size of the test array. The mean difference of the PSEs between the test and control arrays was ~ 0.18° of visual angle, or ~6% of the overall radius of the array.

Experiment 2: Binding Ring Size - Methods

Experiment 2 was performed to investigate the effects of altering the size or location of the binding ring relative to the constant circular array stimuli. As in experiment 1, stimulus presentation time was 500ms and the reference array had a fixed radius of 3°. However, the reference also had a binding ring (3°) present, and the method of constant stimuli was replaced with a staircase procedure. Participants completed 20 total staircases in pseudorandom order. The starting radius of each staircase (both test and control) was randomly selected to equal a value either distinctly smaller (2.0° - 2.5°) or distinctly larger (3.5° - 4.0°) than the reference array radius. Four separate staircases were run for five distinct conditions defined by the radius of the binding ring, 2°, 2.67°, 3°, 3.33° or 4°. It is also important to note that given the size of the component circles (0.5°), the binding ring did not overlap with the array in the smallest or largest conditions (2° or 4°). On each trial, participants completed the same 2AFC task from experiment 1, indicating which stimulus had appeared larger. In accordance with standard staircase procedures, the size of the test array was adjusted by a step size ranging randomly from 2 to 5 pixels (0.07° to 0.18°) in the direction opposite of the participant's response. The staircase finished when four reversals were recorded.

Experiment 2: Binding Ring Size - Results

For each staircase the mean of the four reversal points was calculated (the PSE of that individual staircase), and then overall PSE for each condition was obtained by averaging the four staircase PSEs derived from said condition. Although using a different experimental paradigm, the measured effect when the binding ring had a radius of 3.0° (identical to experiment 1) is comparable to the results of experiment 1 (0.16° vs. 0.18°). The results in figure 9 (below) illustrate that the size of the binding ring had a significant influence on perceived size (repeated measures ANOVA: $F(4, 36) = 31.22$, $p < .001$).

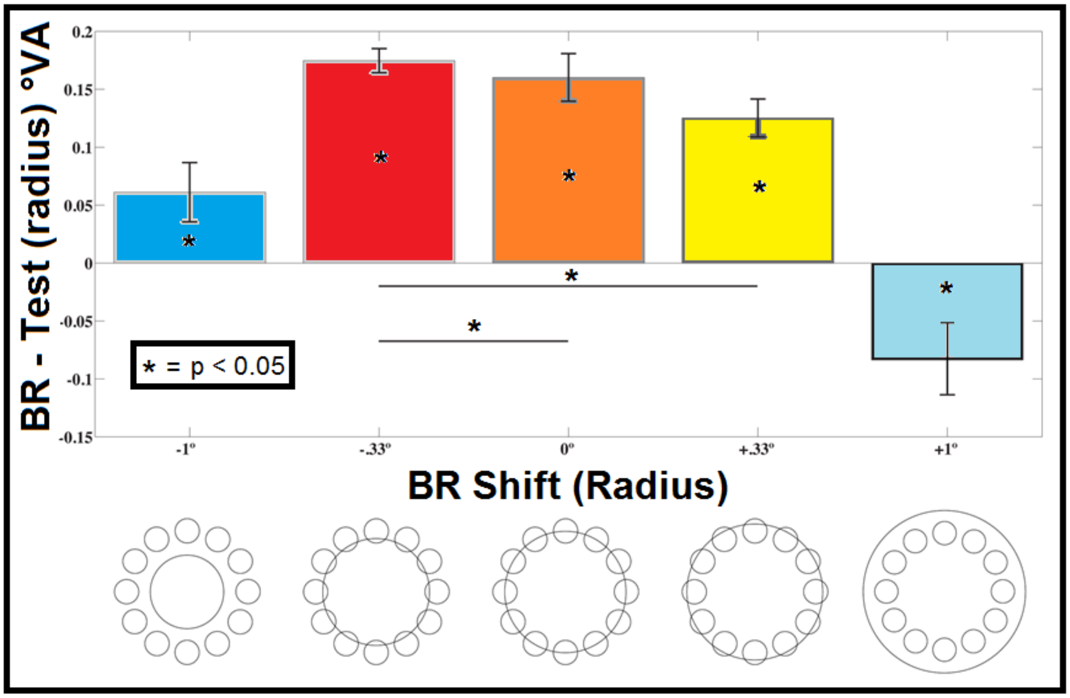

Figure 9. Stimuli and results of experiment 2. Binding ring radii from left to right: 2º, 2.67º, 3º, 3.33º and 4º; array radius was 3º. The graph illustrates the PSEs for the each stimulus type. Significant PSE interactions were indicated by an asterick. Lower asterisks/lines indicate significant ($p < 0.05$) differences, based on post-hoc paired t-tests. A positive PSE (conditions 1-4) indicates illusory shrinkage, whereas a negative PSE (condition 5) indicates illusory growth.

Specifically, the array elements were assimilated toward the location of the binding ring. Furthermore in each of the five conditions, the perceived size of the array was significantly influenced by the presence of the binding ring (one sample two-tailed, t-tests: all $p < 0.05$ uncorrected). The size of the array was perceived as being smaller in the four conditions in which the binding ring radius was smaller than the radius of the exterior portion of the array. However, in the condition where the binding ring completely encompassed the array, the perceived size of the array was larger than when no binding ring was present, a reversal of the effect in the other four conditions. It is of particular interest that the magnitude of the effect is greatest when the binding ring is superimposed on the array (i.e. intersecting). A follow up comparison of the three overlapping conditions vs. the two non-overlapping conditions revealed the magnitude of the illusory effect is significantly larger when the binding ring intersects the array ($F(1, 9) = 50.87$, $p < .001$). Further, a second repeated measures ANOVA examining only the three superimposed conditions revealed that the size of the binding ring (within the intersecting range) significantly influences the magnitude of the illusion ($F(2, 18) = 3.84$, $p < .05$). As can be seen in figure 9 (below), the magnitude of the illusion increases as the size of the binding ring is reduced for the three superimposed conditions (conditions 2-4) – meaning that the magnitude of the illusion is inversely proportional to the size of the binding ring. Together, these effects are consistent with the effects of assimilation.

Experiment 3: Spatial Frequency - Methods

Spatial frequency has been shown to affect the perception of depth, and size constancy relates perceived depth and perceived size (Brown & Weisstein, 1988; Bennett & Cortese, 1995). It follows that spatial frequency information could be affecting the misperceived size inherent in the binding ring. As such, experiment 3 investigated the role of spatial frequency in by altering the spatial frequency information available in the stimuli. Experiment 1 was used as a basis, with the original stimuli being put through either a low or high pass filter (left / right stimuli sets respectively, figure 10A, below). The high-pass cutoff was set at (2 cpd) for the high spatial frequency (HSF) stimuli and the low-pass cutoff was set at (0.5 cpd) for the low spatial frequency (LSF) stimuli. In each presentation the test and reference stimuli were put through the same filter. Overall the experiment used (9 by 2 by 2 =) 36 different trial types – 9 test radii (identical to experiment 1), a test or control array (bound or unbound), and two spatial filters (high and low).

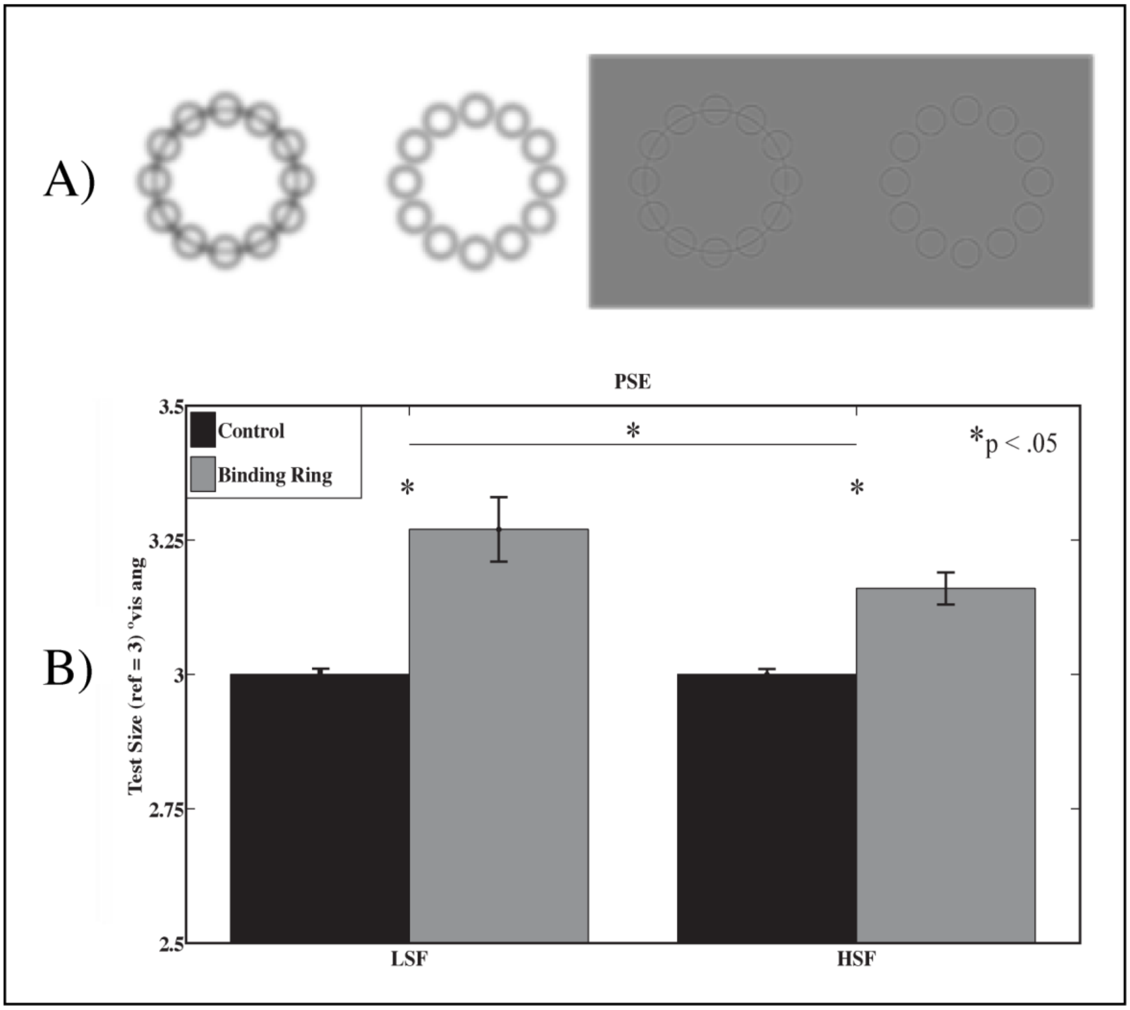

Figure 10. Stimuli and results of experiment 3. A) High- and low-pass versions of the Binding Ring stimuli. B) Results of experiment 3. The PSE of both HSF and LSF conditions are plotted for both the control and Binding Ring conditions. Error bars represent standard error of the mean.

Experiment 3: Spatial Frequency - Results

After fitting the generated psychometric curves using the same procedures described in experiment 1, a 2 (Binding Ring vs. Control) × 2 (HSF vs. LSF) repeated measures ANOVA was conducted, revealing a significant effect of the binding ring on perceived size ($F(1, 11) = 27.05$, $p < .01$), a significant effect of spatial frequency on perceived size ($F(1, 11) = 12.30$, $p < .01$) and finally a significant interaction between the binding ring and spatial frequency ($F(1, 11) = 5.57$, $p < .05$). As can be seen in Figure 10B above, for both low- and high-pass stimuli, the array containing the binding ring was perceived to be smaller compared to when no binding ring is present. It should also be noted that this effect is significantly greater when the stimuli are low-pass filtered in comparison to high-pass filtered. Further, the size of the effect observed for the LSF condition (~0.3º) was larger than that observed in the previous experiments that ranged from 0.16º – 0.18º. However, when the stimuli were high-pass filtered, the resultant ~0.2º reduction in perceived size is comparable to the measured illusory effect in the analogously sized experiments 1 and 2 (condition 3).

Experiment 4: Array Component Size - Methods

Experiment 4 was conducted to investigate the role of the size of the smaller component elements of the circular array. The stimuli and procedures used were similar to those used in experiment 1, with minor modifications. Three separate test array conditions were used; the difference between them was the modified component circle radius (0.2°, 0.5°, or 0.8° VA). Furthermore, the range of possible radii for the test and control arrays were increased by 1° VA to prevent component circle overlap, meaning the possible radii were: 3.5°, 3.625°, 3.75°, 3.875°, 4.0°, 4.125°, 4.25°, 4.375° or 4.5° VA. In order to maintain stimuli separation similar to E1 and ensure accurate results, the increase in possible radii necessitated increasing the radius of the reference array to 4° VA and furthering the stimulus distance from the central fixation to 7.25° VA total.

Experiment 4: Array Component Size - Results

As can be seen in figure 11 (below), the results of experiment 4 were not conclusive aside from reaffirming the fact that a binding ring leads to a perceptual decrease in array size. The error bars were very large (exceptionally so on the small component condition), and further, no apparent pattern can be derived from the various PSEs. Additionally, if the magnitude of the illusion increases as the area over which assimilation occurs increases, one would expect the largest condition (0.8°) to show the largest effect – but this is not the case. Given the high amount of error seen in addition to results inconsistent with the previous experiments, this calls for additional research in the future.

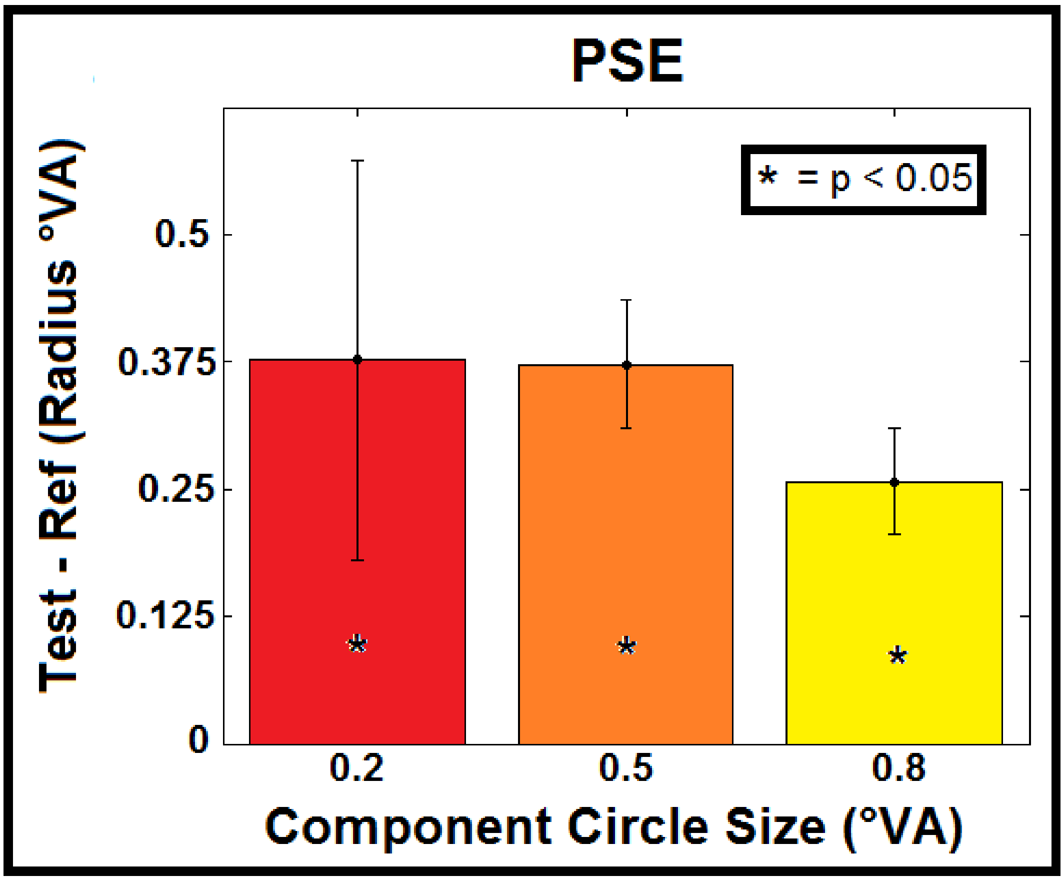

Figure 11. PSEs of Experiment 4. The difference in PSE between the test and control conditions is shown for the three different radii of the component circles, 0.2°, 0.5°, and 0.8° VA.

Experiment 5: Binding Ring Configurations - Methods

Experiment 5 was conducted identically to experiment 1, with one exception: the local configuration of the test (bound) array was altered such that only certain portions of the binding ring were present in the test stimuli. Two configurations were simultaneously (and pseudorandomly) tested: only the linking portions present (figure 12A), or only the interior portions present (figure 12B).

Experiment 5: Binding Ring Configurations - Results

The PSEs provided in figure 12C/D were created with the same curve fitting method described in experiment 1. A paired samples t-test between the PSEs of the linking-only condition (figure 12C) revealed no significant difference in perceived size ($t(4) = 2.05$, *ns*). Similarly, a paired t-test between the PSEs of the interior-only condition (figure 12D) showed no significant difference in perceived size ($t(4) = 1.93$, *ns*).

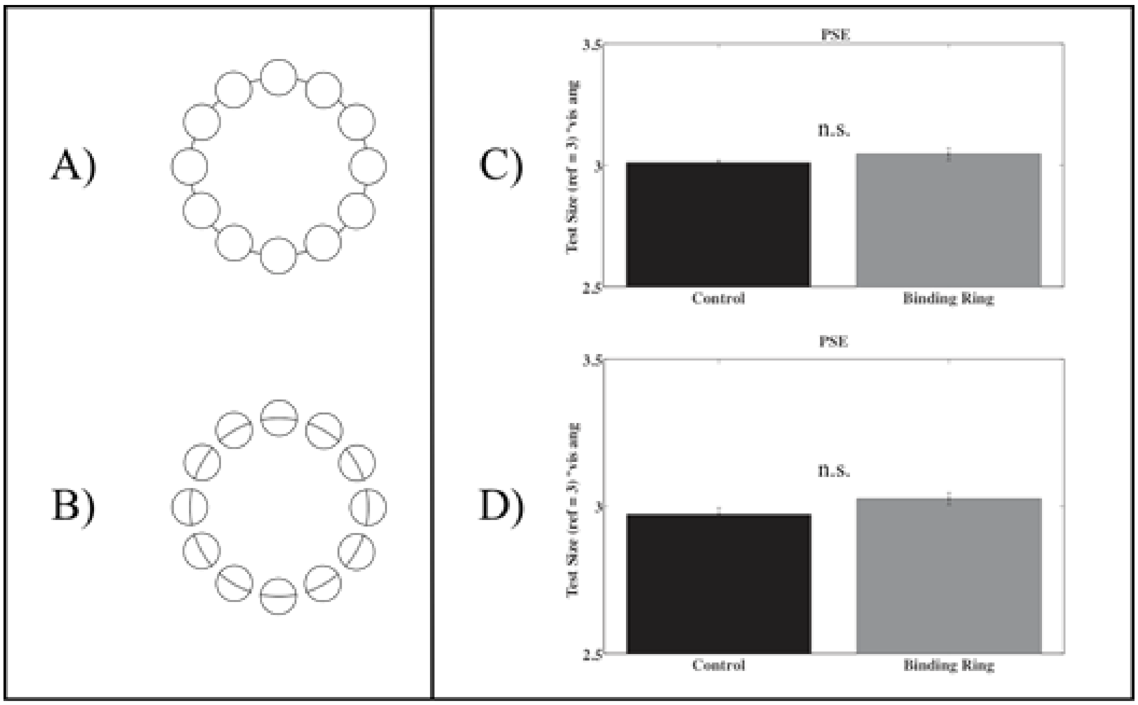

Figure 12. Stimuli and results of experiment 5. A) Linking-only binding ring stimulus. B) Interior-only binding ring stimulus. C) PSEs of the linking-only condition. D) PSEs of the interior-only condition.

Discussion: General Implications

First, experiment 1 confirms the binding ring stimulus does indeed create a perceptual illusion leading to misperceived size. Furthermore, experiment 2 shows that A) said illusory effect is mainly explained by theories of assimilation and B) the size and location of the binding ring relative to the circular array has a significant influence on the illusion magnitude. Taken together, the findings of experiment 2 agree with the assimilation theories posited to explain stimuli similar to the binding ring, i.e. the Delbouef and Ebbinghaus illusions (Coren and Girgus, 1978; Robinson, 1972). Additionally, experiment 3 shows the illusory magnitude of the binding ring is significantly larger when the stimuli are low pass filtered (~0.3°) vs. the high pass (~0.2°) or full spectrum (E1: ~0.16°; E2, condition 3: ~0.18°) stimuli. Finally, experiment 5 shows a complete loss of illusory effect when binding ring is decomposed into its connecting or interior elements, showing that the entirety of the binding ring is necessary for the illusory effect.

Discussion: The Binding Ring Illusion Occurs through Assimilation

The results of experiment 2 indicate that the observed illusory alteration of array size in the binding ring is largely due to assimilation: as the binding ring shifted towards the inside of the array, the magnitude of the illusion increased as assimilation had to take place over a larger area. Further supporting the idea of assimilation are the conditions in experiment 2 in which the binding ring did not intersect the array (conditions 1 and 5): the PSEs of said conditions indicate significant size alteration in a manner consistent with assimilation theory, meaning the size of the array was biased towards the location of the binding ring. These findings agree with the classic assimilation effects observed in the Delbouef illusion – when the outer ring is proximal to the inner elements, the array and circle are more easily seen as a single object ('unification'), which increases the bias of the inner elements towards the outer circle. (Coren and Girgus, 1978; Goto et al, 2007; Robinson, 1972). Interestingly, these findings disagree with the contrast explanation of the Ebbinghaus Illusion, and instead provide an alternative explanation based on assimilation. Typically, the Ebbinghaus illusion is interpreted as occurring because the interior circle of the larger stimulus is being contrasted with the size of its surrounding elements, thereby decreasing its apparent size (Coren and Girgus, 1978; Goto et al, 2007; Robinson, 1972); however, the results of this experiment indicate the possibility that it is not occurring because of the underestimated size in the large stimulus, but rather the *overestimated* size in the smaller stimulus (as it is assimilated towards the proximal components).

Additionally, the findings of experiment 2 further concur with predictions from assimilation theory based on the idea of 'area of assimilation,' or the area over which assimilation occurs. When comparing only the intersecting conditions (2-4), the magnitude of the illusion significantly increased as the size of the binding ring decreased (Coren and Girgus, 1978, Goto et al, 2007, Robinson, 1972). This inversely proportional relationship likely occurs because as the binding ring decreases in size, the process of assimilation takes place over a larger area (from binding ring to the outermost edge of the component elements), thereby increasing the illusory magnitude.

<u>Discussion: Spatial Frequency Differences</u>

The results of experiment 3 indicate that the illusory effect of the binding ring is larger when low-only spatial frequency information is available (~0.3°), as opposed to high-only (~0.2°) or full spectrum (~0.18°) . Technically these findings are consistent with LSF hypotheses for some size illusions (Carrasco et al, 1986); however, a spatial frequency based explanation for the binding ring illusion is unlikely. First, the magnitude of the illusion (~0.2°) in the HSF domain is consistent with the illusory magnitude of full spectrum stimuli (E1: ~0.16°; E2, condition 3: ~0.18°). Unfortunately, the most likely explanation for the differences in LSF and HSF illusory magnitudes is an artifact of the filtering process – the 'blurring' (inherent to creating LSF stimuli) of the original image creates a final stimulus wherein the elements are actually larger (~0.4° VA in radius vs. 0.25° VA in the original) than they were in the full spectrum of HSF stimuli. This blurring effectively increases area of assimilation, which as previously shown increases the overall magnitude of the illusion. Similarly, assimilation remains a viable explanation for the HSF findings – as the HSF stimuli were effectively the same size as the full spectrum stimuli, the results show the illusory effect as being nearly identical, as would be expected. Despite the unlikeliness of a spatial frequency account for the binding ring illusion, experiment 3 provided two extremely useful results: first, it helps to further support the hypothesis of assimilation, and second, helps to refine the idea of where assimilation occurs in the visual processing stream. Assimilation was present in both the HSF and LSF conditions, implying that said assimilation must either be happening concurrently in both the HSF and LSF processing streams (unlikely – added complexity with no gain) or at a stage following spatial frequency integration (likely – more simple, consistent with the top-down visual stream processing paradigm).

Discussion: Perceptual Unification

Further supporting the assimilation hypothesis is the concept of perceptual unification. Recent studies have shown that the magnitude of assimilation can be heavily influenced by a process referred to as unification, which occurs when the component elements of as stimulus are perceived as belonging to a single object (Goto et al, 2005; 2007) - findings which are entirely consistent with the results of experiment 2. While illusory effects are observed in the non-intersecting conditions (1,5), the magnitude of the illusion is significantly larger when the binding ring intersects the array (conditions 2,3,4), and thereby encourags the unification of the array elements and binding ring into one object. The same research (Goto et al, 2005; 2007) also raised the hypothesis that the separate assimilation and contrast effects seen in classic geometric illusions (i.e. Delbouef or Ebbinghaus, both of which could be considered binding ring variants) arise due to the percept of the stimulus elements as either separate objects or a unified whole. Combined with the results of experiment 5, this idea – the prominent role of unification in assimilation – seems quite likely. Given the lack of observed illusion in the altered configurations variants of the binding ring, it is likely the observed effects occur due to the perceptual representation of the component elements of the stimulus as one unified object. It appears that the entirety of the superimposed binding ring is necessary to generate the illusion – decomposing the binding ring removes unification, and therefore removes assimilation, the primary illusory process.

Conclusions:

The illusory effect of the binding ring is now scientifically established, as experiment 1 shows a ~6% decrease in the perceived size of an array radius when coordinated with a binding ring. Further, the results of experiment 2 provide a compelling argument for assimilation as an explanation of the illusion, a hypothesis supported by both the significant increase in the illusory effect concurrent with increasing area of assimilation, and the fact that assimilation remains when the binding ring is completely inside or outside the array. Further supporting the assimilation explanation of the binding ring illusion are the results which agree with unification (E2, E5), as it was found that ease of perceptual unification (i.e. binding ring intersection) increases the magnitude of the assimilation-based illusion, and further that some degree of unification is necessary to generate any illusory effect (as configural alterations led to loss of illusion).

Taken together, these results indicate that the binding ring illusion is occurring primarily through a process of assimilation, and further, this assimilation is heavily influenced by a process perceptual unification of the stimuli components.

Finally, the results of experiments 3 and 5 provide some insight into the location of the assimilation mechanism in the visual processing stream. Seen in experiment 3, assimilation occurs in both high and low spatial frequency domains, an observation which indicates the assimilation processes are occurring somewhere in the visual processing stream following spatial frequency integration. Additionally, the lack of illusion in experiment 5 indicates that local configural features are not responsible for the binding ring illusion; when combined with the findings that support the role of perceptual unification, the most likely hypothesis is that the process of assimilation occurs on a relatively large (possibly global) scale within the visual processing stream – further supporting the theory that assimilation is located in a relatively high position in the visual processing stream.

Now to return to the overarching question of the thesis – how do we perceive the size of different objects? This research has shown that our perception of an object's size can be heavily influenced by processes of assimilation, which are located high in the visual processing stream. Furthermore, these effects of assimilation are mediated by perceptual unification processes – likely occurring prior to assimilation, but following local form processing and spatial frequency integration.

Future Research:

As I had initially hoped, the experiments performed in this investigation successfully quantified the binding ring illusion, in addition to providing a well-supported explanation of said illusion – in this case, the processes of assimilation and unification. That being said, there remains a large amount of potential research to be found in the binding ring illusion and variants thereof.

One potential experiment would be to investigate the effects of color differences on the binding ring illusion – an experiment which would complement the experiments performed here, as it would show if color plays a role in assimilation or unification, and further, where the assimilation and unification processes are occurring in the visual processing stream relative to color processing.

Additionally, the lack of a feasible explanation for the results of experiment 4 (component sizes) opens up a rather large number of possible experiments. Some examples would be: a more advanced component size alteration study, a study investigating the illusory effect in relation to the ratio of component and binding ring sizes, or a study investigating the effects of 'array density,' i.e. the proportion of the array circle that contains an element.

Similarly, investigations could be done on the role of explicit and implicit information on object size perception. It is entirely possible that the illusory effect measured above was not due to the shrinkage of the bound array, which contains explicit size information (in the form of the binding ring), but rather due to the *overestimation* of the unbound array, and implicit size inference.

Finally, another giant avenue of research would be to investigate the illusory effects of the binding ring in relation to depth. For example, would the illusion exist if the stimuli were presented as being in different planes (i.e. one looks farther away than the other)? Or perhaps there is an inherent perception of relative depth (i.e. repeat experiment 1 but ask “which one looks farther away?”) While more technically advanced, as presentation programs would have to integrate 3d technology, the results could be extremely interesting with respect to the idea of size constancy, as size constancy is derived from the interaction of size perception and depth perception. The binding ring has been proven to alter size perception - what role would that misperceived size play in depth perception?

References:

Bennett PJ, & Cortese, F. (1995) Masking of spatial frequency in visual memory depends on distal, not retinal, frequency. *Vision Res,* 36(2), 233-238.

Brainard, D. H. (1997) The Psychophysics Toolbox, *Spatial Vision,* 10, 433-436.

Brown, J.M., & Weisstein, N. (1988) A spatial frequency effect on perceived depth. *Perception & Psychophysics,* 44(2), 157-166.

Carrasco M, Figueroa J. G., Willen J. D., (1986) A test of the spatial-frequency explanation of the Müller-Lyer illusion. *Perception*, 15, 553-562

Coren, S., Girgus, J.S., Erlichman, H., Hakistan, A.R., (1976) An empirical taxonomy of visual illusions. *Perception and Psychophysics,* 20, 129-137

Coren, S., Girgus, J.S., (1978*) Seeing is Deceiving: The Psychology of Visual Illusions* (Hillsdale: Lawrence Erlbaum Associates)

Delboeuf, J. (1893)"Sur une nouvelle illusions d'optique. *Revue Scientifique*, 51, 237-241

Ebbinghaus, H. (1902) Grundzüge der Psychologie volumes I and II Leipzig: Verlag von Viet and Co

Gescheider, G. (1997). *Psychophysics: the fundamentals (3rd ed.).* "Chapter 3: The Classical Psychophysical Methods". Lawrence Erlbaum Associates.

Goto, T., Uchiyama, I., Imai, A., Takahashi, S., Hanari, T., Nakamura, S., Kobari, H. (2005) "Assimilation and contrast" *In Handbook of the Science of Illusion Goto and Tanaka*, Eds. Tokyo: Tokyo University Press pp. 164-176

Goto, T., Uchiyama, I., Imai, A., Takahashi, S., Hanari, T., Nakamura, S., & Kobari, H. (2007) Assimilation and contrast in optical illusions. *Japanese Psychological Research,* 49(1), 33-44.

Girgus, J.S., & Coren, S. (1982) Assimilation and contrast illusions: Differences in plasticity. *Perception & Psychophysics*, 32(6), 555-561

Gruber, H.E. (1954) The relation of perceived size to perceived distance. *The American Journal of Psychology,* 67(3), 411-426.

Helmholtz, H. von. (1867/1962) Treatise on physiological optics (J.P.C. Southall, Ed.). Translation of the 3rd German ed. New York: Dover. (*cited in Walsh & Kulikowski, 1998)*

Hermann, L. (1870) Eine Erscheinung simultanen Contrastes. *Pflügers Archiv für die gesamte Physiologie* 3: 13–15. doi:10.1007/BF01855743

Kaufman, L., Kaufman, J.H., Noble, R., Edlund, S., Bai, S., & King, T. (2006) Perceptual distance and the constancy of size and stereoscopic depth. *Spatial Vision*, 19(5), 439-457.

King, D., & Wertheimer, M. (2005). *Max wertheimer & gestalt theory*. New Brunswick, NJ: Transaction Publishers.

Köhler, W. (1929). *Gestalt psychology*. Rahway, NJ: Quinn & Boden Company, INC.

Kubzansky, P.E., Rebelsky, F., and Dorman, L. (1971) A developmental study of size constancy for two- versus three-dimensional stimuli. *Child Development,* 42, 633-635.

Lawson, R., Bertamini, M., and Liu, D. (2007) Overestimation of the Projected Size of Objects on the Surface of Mirrors and Windows. *Journal of Experimental Psychology: Human Perception and Performance,* 33(5), 1027-1044.

Lehar, S. (2004) Gestalt Isomorphism and the Primacy of Subjective Conscious Experience: A Gestalt Bubble Model. *Behavior & Brain Sciences,* 26(4), 375-444.

Mandler, G. (2007) *A history of modern experimental psychology*. Cambridge, MA: Bradford.

McCarthy, J.D., Kupitz, C.N., and Caplovitz, G.P. (2011) The Binding Ring Illusion: Assimilation affects the perceived size of an array. submitted to *iPerception*

Müller-Lyer, F.C. (1889) Optische Urteilstäuschungen. *Archiv für Physiologie Suppl*.,263–270.

Peterman, B., translated by Fortes, M. (1932). *The gestalt theory and the problem of configuration*. Norwich: Jarrold and Sons Limited.

Ponzo, M. (1912) Rapports entre quelques illusions visuelles de contraste angulaire et l'appreciation de grandeur des astres 11 I'horizon. *Archives Italiennes de Biologie,* 58, 327-329.

Reiner, L. & De Volder, A. (2005) Cognitive and brain mechanisms in sensory substitution of vision: a contribution of the study of human perception. *Journal of Integrative Neuroscience,* 4(4), 489-503.

Robinson, J.O. (1972) The Psychology of Visual Illusion (London: Hutchinson)

Spillmann L, (1994) The Hermann grid illusion: a tool for studying human perceptive field organization. *Perception*, 23(6) 691-708.

Wade, N. J. (1998) *A Natural History of Vision*. Cambridge, MA: The MIT Press.

Walsh, V., & Kulikowski, J. (1998) *Perceptual constancy: why things look as they do*. Cambridge: Camridge University Press. pp. 499-528 (Chapter 18: The history of size constancy and size illusion.

Appendix:

Provided below in figure 13 is an example of the data graphs created in each experiment; this contains all subjects in Experiment 1. The curves therein were compared within-subject to generate his/her PSE, as described in Experiment 1 (pg. 11); the PSEs were then averaged across subjects to obtain the mean PSE for the experiment (as in figure 8). Only the derived PSE data (the purpose of the graphing and data interpretation) are shown for the remaining experiments.

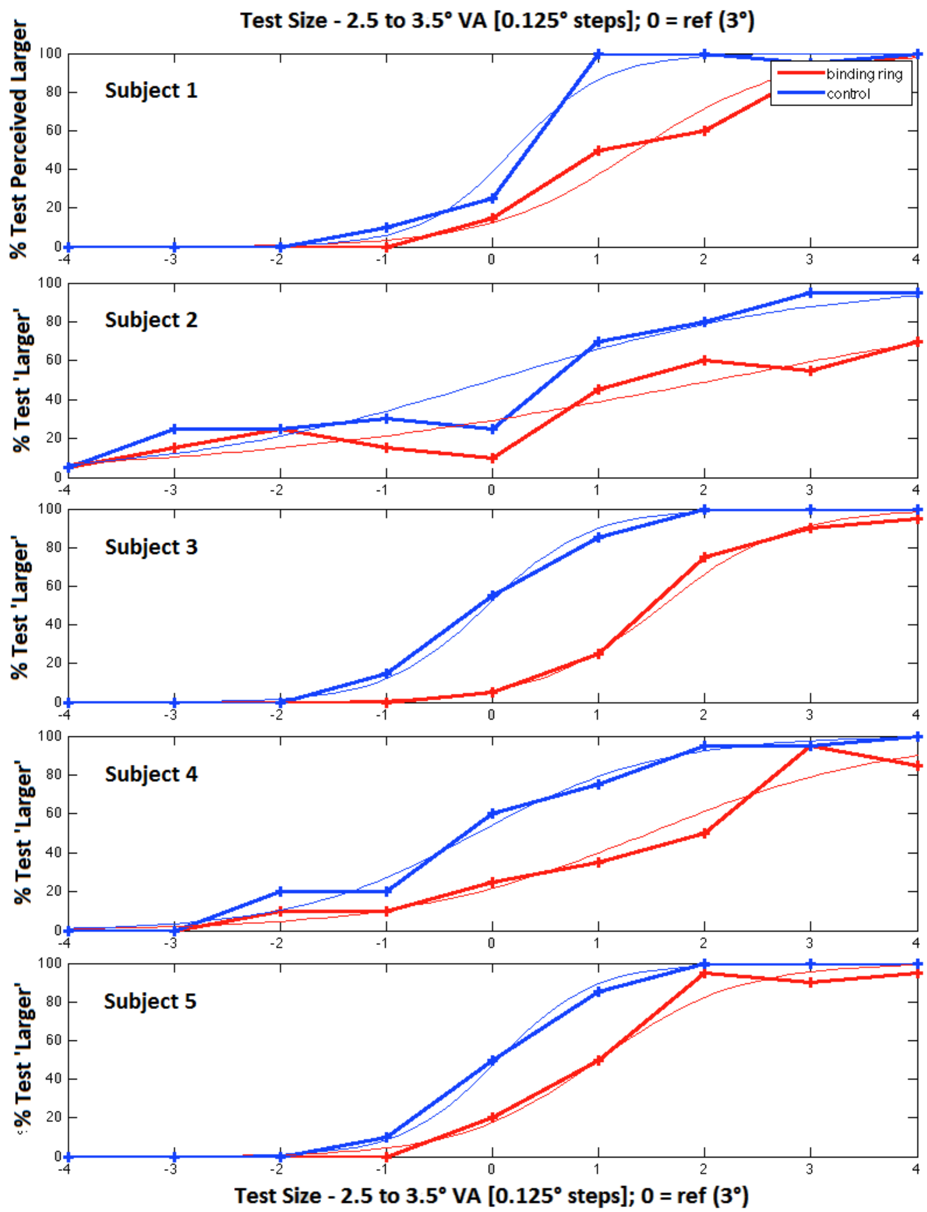

Figure 13. Data and derived psychometric curves of Experiment 1. Each graph represents the data of each participant; each data point represents the how often the participant perceived the test as large (in percentages). Red represents the 'binding ring' condition, and blue represents the 'control' condition. Bold lines are the data (table below), with '+' marking each condition. Thin lines represent the extrapolated psychometric curve for the respective condition.

Table 1: Full data and derived PSEs from Experiment 1 - Quantification

BR = Binding Ring			Test Size (°VA); Ref = 3°									PSE (°VA)
CTL = Control			2.5	2.625	2.75	2.875	3	3.125	3.25	3.375	3.5	Difference
% Test perceived Larger	Subject 1	BR	0	0	0	0	15	50	60	90	100	**0.17**
		CTL	0	0	0	10	25	100	100	95	100	**0.02**
	Subject 2	BR	5	15	25	15	10	45	60	55	70	**0.26**
		CTL	5	25	25	30	25	70	80	95	95	**0.00**
	Subject 3	BR	0	0	0	0	5	25	75	90	95	**0.20**
		CTL	0	0	0	15	55	85	100	100	100	**-0.06**
	Subject 4	BR	0	0	10	10	25	35	50	95	85	**0.18**
		CTL	0	0	20	20	60	75	95	95	100	**-0.02**
	Subject 5	BR	0	0	0	0	20	50	95	90	95	**0.13**
		CTL	0	0	0	10	50	85	100	100	100	**0.01**

Table 2: PSEs from Experiment 2 – Binding Ring Size

PSE Difference (BR - CTL)	Subject:	Binding Ring Size (°VA)				
		2.00	**2.67**	**3.00**	**3.33**	**4.00**
	1	0.13	0.15	0.21	0.12	0.00
	2	-0.02	0.18	0.19	0.06	0.01
	3	-0.04	0.18	0.19	0.07	-0.11
	4	0.04	0.20	0.21	0.20	-0.19
	5	0.14	0.22	0.20	0.19	-0.03
	6	0.11	0.17	0.20	0.17	0.02
	7	0.09	0.17	0.12	0.13	-0.16
	8	0.10	0.15	0.20	0.23	0.11
	9	-0.04	0.16	0.17	0.12	-0.24
	10	0.16	0.20	0.06	0.09	-0.09

Table 3: PSEs from Experiment 3 – Spatial Frequency

Subject:	Low Pass PSE (°VA)		High Pass PSE (°VA)	
	BR	*CTL*	*BR*	*CTL*
1	3.15	3.02	3.18	3.02
2	3.28	2.99	3.12	2.97
3	3.18	3.00	3.07	2.97
4	3.25	3.01	3.19	2.99
5	3.82	2.97	3.40	3.04
6	3.21	3.02	3.25	2.97
7	3.15	3.05	3.12	3.01
8	3.09	2.98	3.04	3.04
9	3.41	3.01	3.29	2.99
10	3.23	2.98	3.06	3.00
11	3.21	2.99	3.10	3.01
12	3.21	2.98	3.15	2.97

Table 4: PSEs from Experiment 4 – Component Size

Subject:	Component Size					
	0.2 (°VA)		0.5 (°VA)		0.8 (°VA)	
	BR	*CTL*	*BR*	*CTL*	*BR*	*CTL*
1	0.55	0.18	1.32	0.19	0.50	-0.04
2	0.46	-0.77	2.16	-0.63	1.72	0.46
3	2.81	0.32	2.79	-0.37	2.54	0.10
4	9.74	-0.24	4.03	-0.44	2.62	-0.19
5	2.49	-0.04	2.54	-0.10	2.57	0.03
6	1.38	-0.10	3.58	-0.11	2.33	-0.43

Table 5: PSEs from Experiment 5 – Binding Ring Configurations

Subject:	Configurational PSEs (°VA)			
	Linking-Only		Interior-Only	
	BR	*CTL*	*BR*	*CTL*
1	0.11	0.04	0.00	-0.07
2	0.04	-0.01	0.07	-0.08
3	-0.03	0.02	-0.03	-0.01
4	0.04	0.01	0.18	-0.02
5	0.06	-0.01	0.03	-0.01