



RESEARCH ARTICLE

UPDATED The Binding Ring Illusion: assimilation affects the perceived size of a circular array [v2; ref status: indexed, <http://f1000r.es/12q>]

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Abstract

Our perception of an object's size arises from the integration of multiple sources of visual information including retinal size, perceived distance and its size relative to other objects in the visual field. This constructive process is revealed through a number of classic size illusions such as the Delbouef Illusion, the Ebbinghaus Illusion and others illustrating size constancy. Here we present a novel variant of the Delbouef and Ebbinghaus size illusions that we have named the Binding Ring Illusion. The illusion is such that the perceived size of a circular array of elements is underestimated when superimposed by a circular contour – a binding ring – and overestimated when the binding ring slightly exceeds the overall size of the array. Here we characterize the stimulus conditions that lead to the illusion, and the perceptual principles that underlie it. Our findings indicate that the perceived size of an array is susceptible to the assimilation of an explicitly defined superimposed contour. Our results also indicate that the assimilation process takes place at a relatively high level in the visual processing stream, after different spatial frequencies have been integrated and global shape has been constructed. We hypothesize that the Binding Ring Illusion arises due to the fact that the size of an array of elements is not explicitly defined and therefore can be influenced (through a process of assimilation) by the presence of a superimposed object that does have an explicit size.

Article Status Summary

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UPDATED Changes from Version 1

In this revised article we address several of the issues raised by the reviewers. We have corrected the references in order to more accurately reflect the historical record. We have included a brief discussion of recent findings suggesting a significant role for the early visual cortex including V1 in representing the perceived size of an object. We have included a broader discussion of other size illusions.

See referee reports

Introduction

Correctly perceiving the size of objects is essential to successfully interact with the world around us. Due to the fact that we sense the 3D visual world through an analysis of 2D retinal images, the process of size perception is intrinsically ambiguous. As a result, the perception of an object's size arises from the integration of multiple sources of visual information including the size of its retinal image, its perceived distance¹, and its size relative to other objects in the visual scene^{2,3}. These constructive processes are revealed through a number of classic size illusions such as the Ebbinghaus Illusion⁴ (Figure 1A), the Delboeuf Illusion^{5,6} (Figure 1B), the Müller-Lyer Illusion⁷ (Figure 1C) and several others that illustrate how mechanisms that underlie size constancy sometimes lead to illusory effects resulting from a discrepancy between retinal and perceived size. In each of these illusions, the perceived size of an explicitly defined object is influenced by the context in which it is presented. Most relevant to the current paper are the Delboeuf and Ebbinghaus illusions that demonstrate that the size of an inner circle is overestimated or underestimated depending on the surrounding context in which it is presented. Though several explanations have been proposed for these illusions, recent research demonstrates that the effect is largely determined by the relative size of the inducer(s), their distance from the target², and in the case of the Ebbinghaus Illusion, the completeness of the surrounding array of elements⁸. Taken together, the balance of these factors determines the magnitude of the illusion and whether the inner circle is overestimated or underestimated.

Here we address the question of how we perceive the size of an implicitly defined object—an array of elements—by introducing a novel variant of the Ebbinghaus illusion that we have named the Binding Ring Illusion. We describe the illusion and investigate the underlying mechanisms that lead to misperceived size. A basic stimulus that elicits perception of the Binding Ring Illusion is composed of a circular array of small circles onto which a larger circle is superimposed as shown in Figure 2A. The superimposed circle leads to an underestimation of the perceived radius of the circular array relative to an equally sized array without the binding ring (Figure 2B). To our knowledge, previous research on the Ebbinghaus Illusion has focused on the effect the surrounding elements have on the explicitly defined circle. Here we consider the possibility of mutual influence in that the inner circle may also lead to misperceived size of the surrounding array. In the following experiments, we investigate the magnitude of this illusory decrease in size and attempt to

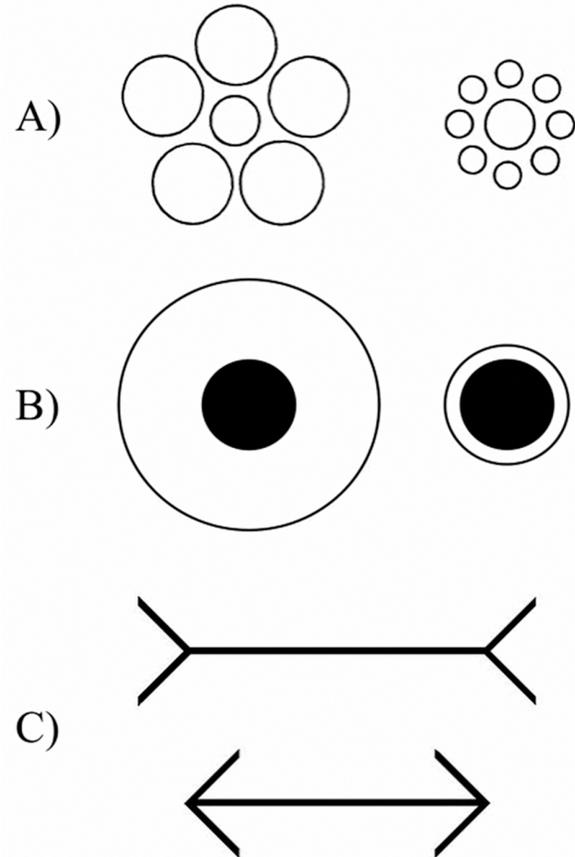


Figure 1. Notable size illusions: **A)** Ebbinghaus illusion, **B)** Delboeuf illusion, **C)** Müller-Lyer illusion.

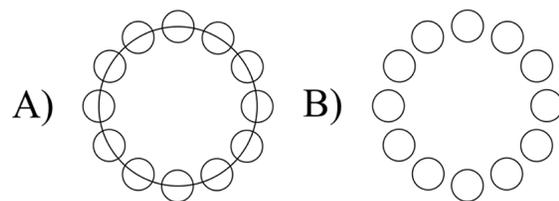


Figure 2. The Binding Ring Illusion. Which array of circles looks bigger? **A)** The test stimulus used in experiment 1 or **B)** The reference stimulus used in experiment 1.

study the components of the stimulus that are responsible for the observed effect.

In experiment 1, we demonstrate that the effect of the binding ring can be quantified. In experiment 2 we demonstrate that the illusion arises due to assimilation toward the binding ring^{9,10}. In experiment 3, we investigated the effect of spatial frequency. Finally, in experiments

4a and 4b we investigated the roles of local configural features in producing the illusion.

General methods

Participants

Five observers (3 men, 2 women; age range: 18–25; mean age = 20.2) participated in experiment 1, ten observers participated in experiment 2 (4 men, 6 women; age range: 19–28; mean age = 22.4), twelve observers participated in experiment 3 (6 men, 6 women; age range: 18–27; $M = 21.75$) and five observers participated in experiment 4 (3 men, 2 women; age range: 18–25; $M = 20.6$). All participants were naive to the aims of the experiments, reported normal or corrected-to-normal vision and 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.

Apparatus and display

Stimuli were presented on a Dell Trinitron P991 monitor (19 inches, 1024 × 768) with an 85 Hz refresh rate. The stimulus computer was a 2.4 GHz Mac Mini with an NVIDIA GeForce 320M graphics processor (256MB of DDR3 SDRAM). Stimuli were created and presented with the Psychophysics Toolbox¹¹ for MATLAB (Mathworks Inc., Natick, MA). In experiments 1, 2 and 4, the stimuli were white (120 cd/m²) presented on a black (0.06 cd/m²) background. In experiment 3, the stimuli were either low- or high-pass filtered and presented on a grey background (20.5 cd/m²). Luminance values were measured with a Photo Research PR655 spectroradiometer. Participants placed their head on a chin rest and viewed the stimuli binocularly from a distance of 57cm.

Experiment 1

The goal of experiment 1 was to establish a ‘standard’ configuration and quantify the magnitude of the illusion in order to serve as a baseline for further testing. Specifically, we sought to measure the perceived reduction in size of an array superimposed with a binding ring compared to an unbound array of equal size.

Stimuli and procedures

The basic paradigm is illustrated in Figure 3. On a given trial, participants were presented with a small central fixation point (0.35°) for 500ms, followed by the additional simultaneous presentation of two circular arrays (a reference and a test) for 500ms at which point the stimuli were removed from the screen and replaced by a random noise mask displayed for 500ms to discourage afterimages. Participants indicated by pressing one of two buttons (two-alternative forced choice), which of the two stimuli had appeared larger. Each array consisted of 12 small equally spaced circles with radii of 0.05° visual angle. On every trial, the reference array had a fixed radius of 3° visual angle (from the center of the array to the center of any circular element). Using the method of constant stimuli¹², we investigated the perceived size of each of two test arrays compared to the reference array. The test array either had a binding ring superimposed or did not (the lack of a binding ring served as a control condition). In non-control conditions the binding ring had a radius selected to match the radius of the test circular array that was measured from the center of the array to the center of one of the smaller component circles. Because the control array did not

have a superimposed binding ring it was identical to the reference array in all ways except its trial-by-trial size. As such, it was used to determine A) how accurately observers were able to perform the task (discriminate the sizes of the arrays) and B) to serve as a point of comparison for determining the size of the illusory effect. On each trial, the radius of the test array was selected from the following list: 2.5°, 2.6°, 2.8°, 2.9°, 3.0°, 3.1°, 3.3°, 3.4° and 3.5°.

On each trial, the centers of the two arrays were randomly positioned within a circular radius of 1.16° of visual angle centered 6.75° along the horizontal axis to the left or right of the central fixation point. This positional-jitter was used to prevent observers from basing their judgments on horizontal matching or distance comparisons with the edges of the monitor. Participants were instructed to maintain fixation on the center of the screen throughout the experiment. The sides on which the two arrays were presented were randomly determined on each trial. In total there were 18 trial types: nine test radii for both the test and control array types. Trials were pseudo-randomly ordered such that 20 of each trial type were presented in random order for a total of 360 trials. Prior to the experiment, participants were trained on 20 trials of the largest and smallest test array sizes that were not included in the analyses.

Results

For each array size, we computed the percentage of times the test or control array was perceived to be larger than the reference. Thus, for the test (bound) and control (unbound) arrays, nine values (one for each radius) were calculated. Because the 2AFC task has two categorical responses, the following sigmoidal-shaped binomial-logit function was then fit to the corresponding data for each of the two test arrays using the MATLAB (glmfit() command)¹³:

$$f(x) = 100 \times \left[\frac{e^{b_1 + xb_2}}{1 + e^{b_1 + xb_2}} \right]$$

The points of subjective equality (PSE) were determined for each subject by interpolating the 50% chance level from the function fit to the data ($x = -b_1/b_2$). The PSE indicates the size the test array needs to be in order to be perceived as equal in size to the reference. The resulting curves plotted for the mean responses across participants are shown in Figure 4. The clear and steep-sloped sigmoidal shaped psychometric curve derived from the control condition in which neither the reference nor control array have a binding ring confirm that participants were able to perform the task and accurately report their perceptions. Specifically, participants were at chance performance when the two arrays were indeed the same size. The rightward shift of the other psychometric curve, derived from the test (binding ring) condition, demonstrates that the size of the array was underestimated when the binding ring was present. The inset of Figure 4 illustrates the mean points of subjective equality across subjects for the test and control arrays.

A paired t-test between the PSEs of the test and control arrays revealed that the addition of the binding ring significantly ($t(4) = 7.71$, $p < 0.01$) reduced the perceived size of the test array. The mean difference of the PSEs between the test and control arrays was ~0.18°

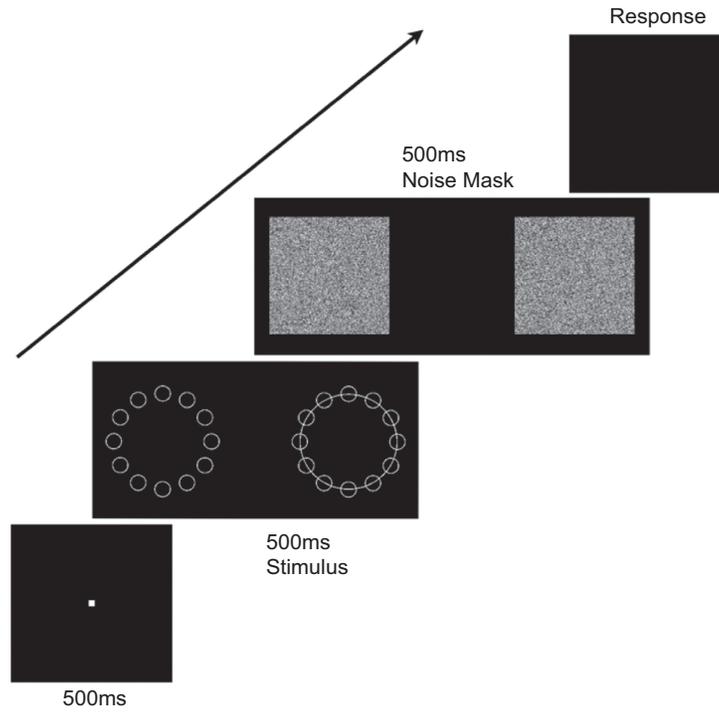


Figure 3. Schematic diagram of a trial in experiment 1. A fixation point appeared for 500ms followed by the presentation of the reference and test array for 500ms at which point the stimuli were removed from the screen and replaced by a noise mask for another 500ms to prevent the formation of afterimages. The screen then remained blank until participants indicated which array appeared larger via a key press.

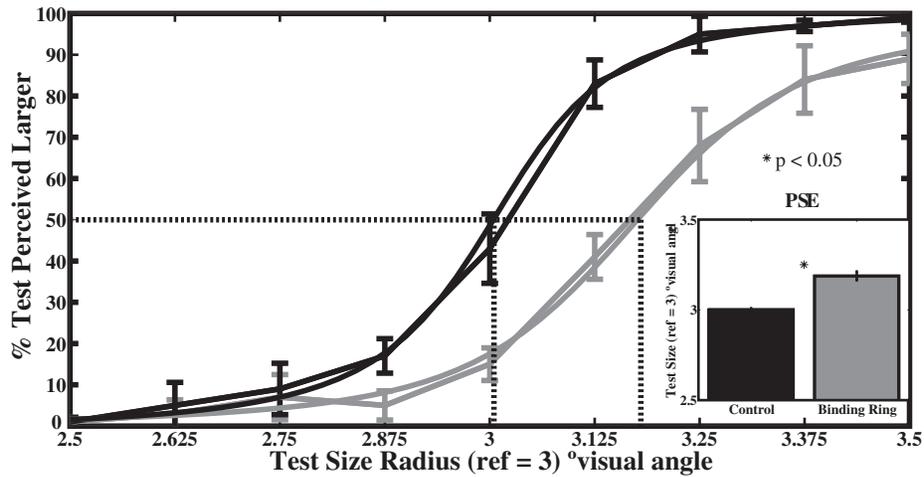


Figure 4. Results of experiment 1. Psychometric curves indicate the mean fit of the data averaged across all participants. The inset of the figure illustrates the mean points of subjective equality (PSEs) for the test and reference stimuli. The black curve indicates that participants were accurately judging the radius of an unbound array. The grey curve shows that the array radius must increase by $\sim 0.18^\circ$ to be perceived as being the same size as an unbound array. Thick curves with error bars indicate the mean response across participants for each array radius. Thin curves indicate the function fitted to the data. Error bars represent standard error of the mean PSE computed across subject.

of visual angle or 6% of the overall radius of the array. Thus, an array superimposed with a binding ring of radius 3.18° was perceived as having the same size as a no-binding ring array with a radius of 3° . This is comparable in magnitude to underestimation effects observed in the classic Ebbinghaus and Delbeuf Illusions^{14,15}.

Experiment 1: Proportion of participants perceiving test arrays as being larger than reference arrays

1 Data File

<http://dx.doi.org/10.6084/m9.figshare.157057>

Experiment 2

Having quantified the magnitude of the illusion in experiment 1, we explored possible mechanisms contributing to the underestimation of perceived size. Size illusions such as the Delboeuf and Ebbinghaus illusions have been explained on the basis of size assimilation (when the size of the element of interest is biased toward the reference component) and contrast (when the size of the element of interest is biased away from the reference component)^{9,10,16,17}. Because the size of an array is not explicitly defined, it remains unclear whether the illusion arises due to assimilation or contrast with the binding ring. In order to determine if the illusion is mediated by assimilation or contrast we investigated the effect of changing the size of the binding ring (bottom of Figure 5). If assimilation is responsible for the effect, we would predict that the magnitude of the illusion should increase as the binding ring gets *smaller*. Alternatively, if the illusion arises due to contrast, the magnitude of the illusion should increase as the binding ring gets *larger*.

Stimuli and procedures

The basic stimuli were the same as those used in experiment 1; however, due to the larger number of configurations tested, we used staircase procedures¹⁸ rather than the method of constant stimuli. The individual trials within the staircases again consisted of a reference and test array simultaneously presented for 500ms. As in the previous experiment, the reference array had a fixed radius of 3° ; however, unlike the previous experiment, the reference contained a binding ring and the test array did not. This was done so as to be able to compare the magnitude of the illusion for a fixed size array across binding-ring sizes. Separate staircases were run for five distinct reference conditions defined by the size of the binding ring with radii chosen from the following list: 2° , 2.67° , 3° , 3.33° and 4° (see Figure 5). Because the radius of each circular element was 0.5° , the binding ring did not physically overlap with the circular array in two of the five conditions and was either entirely inside (2°) or outside (4°) the array. Four staircases were run for each trial type—two in which the initial test or control array was larger than the reference array (descending) and two in which it was initially smaller (ascending). The starting radius for the test or control array was randomly selected to be 0.5° to 1° larger or smaller than the radius of the reference array. On each trial, participants completed a 2AFC task indicating which stimulus had appeared larger. According to standard staircase procedures, the size of the test array was adjusted by a step size ranging randomly on each iteration 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. In total, each participant completed 20 staircases presented in pseudorandom order.

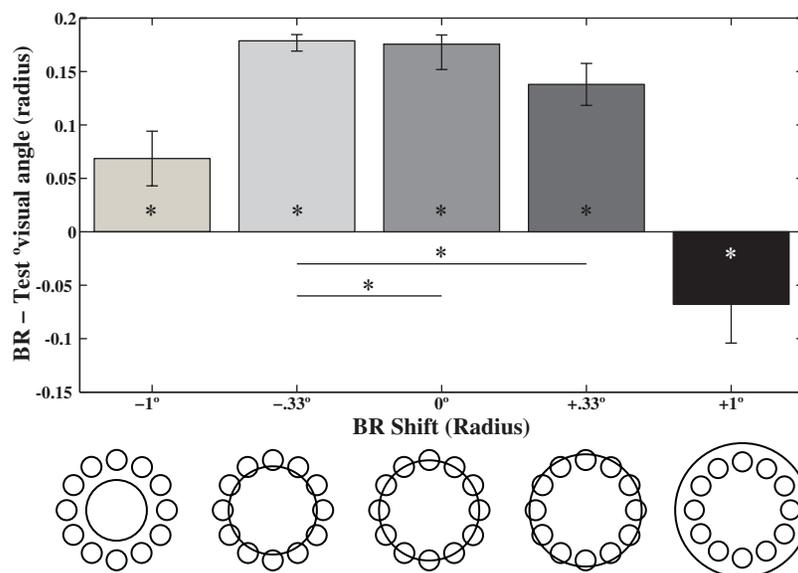


Figure 5. Stimuli and results of experiment 2. The radius of the binding rings from left to right: 2° , 2.67° , 3° , 3.33° and 4° ; circular array radius was consistently 3° . The graph illustrates the PSEs for each stimulus type: lines and asterisks below the bars indicate significant ($p < 0.05$) differences, based on post-hoc paired t-tests, between the three overlapping binding ring conditions. Superimposed asterisks indicate significant changes in perceived size induced by the presence of the binding ring compared to an array without a binding ring (observed for all five conditions). A positive shift on the ordinate axis indicates that the array must increase in size to be perceived as having the same radius as the reference and vice versa. Error bars indicate standard error of the mean.

Results

The mean of the four reversal points was calculated for each staircase and the PSE for each reference condition was obtained by averaging these results across the corresponding four staircases. Although we used a different experimental paradigm than in experiment 1, the size of the measured effect when the binding ring had a radius of 3.0° (same as in experiment 1) is comparable to that observed in experiment 1 (0.16° vs. 0.18°). The results illustrated on the top of [Figure 5](#) indicate:

A) The size of the binding ring had a significant influence on the perceived size of the array (main effect of binding ring size-repeated measures ANOVA: $F(4, 36) = 31.22, p < 0.001$).

B) 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 vs. zero: all $p < 0.05$ uncorrected).

C) The binding ring array was perceived as being smaller than an array without a binding ring in each of the four conditions in which the radius of the binding ring was less than the radius of the exterior portion of the array.

D) 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. This is the reverse effect of the other four conditions.

E) The magnitude of the effect is greatest when the binding ring is superimposed on the array. A follow-up planned comparison of the three overlapping conditions with the two non-overlapping conditions revealed that the magnitude of the effect is significantly larger when the binding ring intersects the array compared to when it does not intersect the array ($F(1, 9) = 50.87, p < 0.001$).

F) A second repeated measures ANOVA examining just the three superimposed conditions revealed that the size of the binding ring (within this range) significantly influences the magnitude of the illusion ($F(2, 18) = 3.84, p < 0.05$). As can be seen in [Figure 5](#), the magnitude of the illusion increases as the size of the binding ring is reduced for the three superimposed conditions. However, once the binding ring becomes too small, such that it no longer overlaps the array, the magnitude of the illusion is greatly decreased. That said, even in this innermost binding ring condition, the perceived size of the array is underestimated. It is noteworthy that this particular stimulus condition is quite similar to that typically used in the Ebbinghaus Illusion (see right side of [Figure 1A](#)). Here we demonstrate that there are in fact two illusory effects revealed in the Ebbinghaus Illusion, one operating on the inner circle (making it appear larger) and one operating on the outer array (making it appear smaller). Taken together, these observed effects are consistent with the assimilation hypothesis and inconsistent with the contrast hypothesis. Furthermore, these results appear to indicate that the outer edge of the circular array is serving as a boundary for the assimilation. When the radius of the binding ring exceeds this boundary, the assimilation bias is to increase the perceived size of the array. Similarly, if the radius of the binding ring is within this boundary, the assimilation bias is to decrease the perceived size of the array.

Experiment 2: reversal choices

1 Data File

<http://dx.doi.org/10.6084/m9.figshare.157058>

Experiment 3

In this and the following experiment, we attempt to identify specific stimulus factors that may influence the Binding Ring Illusion. It is suggested that some visual illusions, including the Müller-Lyer¹⁹ and Oppel-Kundt^{20,21} or filled area illusion²², are mediated by differential processing of low- and high-spatial frequency information^{23–27}. Specifically, differential effects can be obtained resulting in changes to the magnitude of the illusions depending on spatial frequency filtering. Here, we investigated the effect of spatial frequency filtering on the magnitude of the Binding Ring Illusion ([Figure 6A](#)).

Stimuli and procedures

The stimuli and procedures used in experiment 3 were analogous to those used in experiment 1 except that the stimuli were either high- or low-pass filtered. The high-pass cutoff was set at (2 cpd) and the low-pass cutoff was (0.5 cpd). Stimuli were presented on a gray (20.5 cd/m^2) background. In each case, similarly filtered stimuli were compared to each other (i.e. a high spatial frequency (HSF) reference was compared to a HSF test or control). In total there were 36 trial types: nine test radii (same as in experiment 1) for the test and control array types (with and without binding ring) in both HSF and low spatial frequency (LSF) conditions. Trials were pseudorandomly ordered so that 20 of each trial type were presented for a total of 720 trials.

Results

After fitting the curves using the same procedures described above, we conducted a 2 (binding ring vs. control) \times 2 (HSF vs. LSF) repeated measures ANOVA on the derived PSE for each of the four conditions. This analysis revealed a main effect of the binding ring on perceived size ($F(1, 11) = 27.05, p < 0.01$), a main effect of spatial frequency on perceived size ($F(1, 11) = 12.30, p < 0.01$) and a significant interaction between the binding ring and spatial frequency ($F(1, 11) = 5.57, p < 0.05$). As can be seen in [Figure 6B](#), for both low- and high-pass stimuli, the array containing the binding ring was perceived to be smaller than when no binding ring is present. As reflected in the significant interaction, this effect is greater when the stimuli are low- as compared to high-pass filtered. Although the illusion was observed in both the LSF and HSF configurations, the size of the effect observed for the LSF condition ($\sim 0.3^\circ$) is substantially larger than that observed in the previous experiments that range from 0.16° to 0.18° . In contrast, when the stimuli were high-pass filtered, the resultant $\sim 0.2^\circ$ reduction in perceived size is comparable to that observed in the previous experiments.

Experiment 3: perceived size of test and reference arrays at high and low spatial frequency

1 Data File

<http://dx.doi.org/10.6084/m9.figshare.157059>

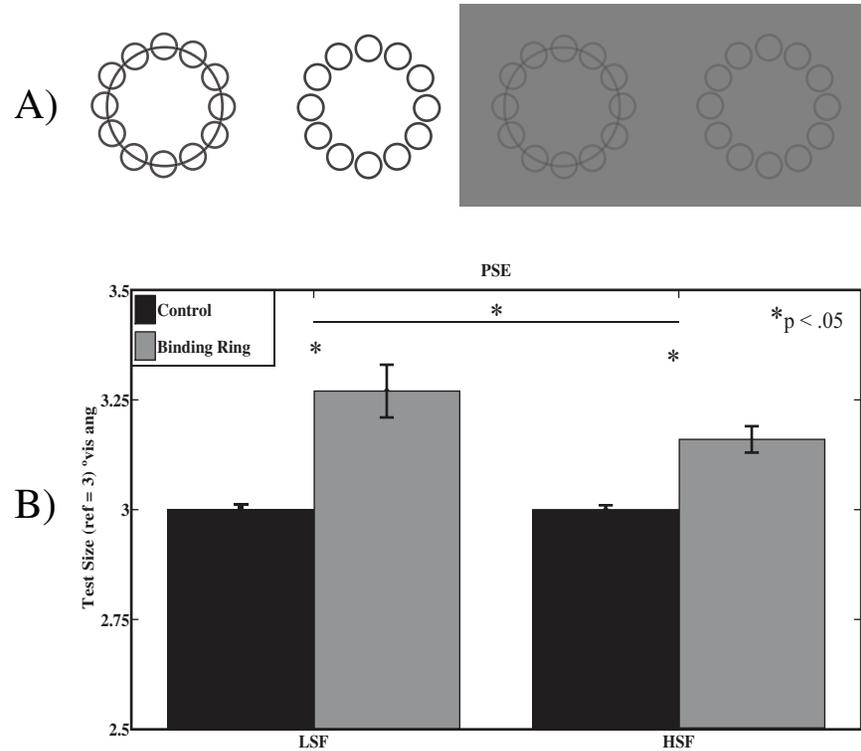


Figure 6. Spatial frequency manipulations. A) Low- (top left) and high-pass (top right) versions of the binding ring stimuli. **B)** Results of experiment 3. The points of subjective equality (PSE) of both high (HSF) and low spatial frequency (LSF) conditions are plotted for both the control and binding ring conditions. Error bars represent standard error of the mean. Asterisks indicate significance at $p < 0.05$.

Experiment 4a

Lastly we investigated the role of the local configural features of the stimulus. A number of visual illusions can be attributed to the processes of local configural features^{3,8,28}. In these two closely related experiments, we investigated the impact of presenting only parts of the binding ring on the presence or magnitude of the Binding Ring Illusion. In doing so we address the question of whether the Binding Ring Illusion is mediated by the processing of specific local features, or perhaps on the basis of more global representations of the objects present in the image.

In the first part of this experiment, the binding ring only connected the array of elements so that it was not visible in the interiors (Figure 7A). In the second part of the experiment, the binding ring was present solely within the interiors of the array elements (Figure 7B) leaving them unconnected from each other.

Stimuli and procedures

The stimuli and procedures used in experiments 4a and 4b were identical to those used in experiment 1 except that in the test condition, the binding ring only connected the array of elements as if viewing a chain of pearls (experiment 4a) or the binding ring was only visible in the interiors of the array elements (experiment 4b).

Results 4a

The data shown in Figure 7C were analyzed using the same curve fitting method described in the results of experiment 1. A paired

samples t-test between the PSEs of the test and control arrays revealed no significant difference in perceived size ($t(4) = 2.05, ns$).

Results 4b

The data shown in Figure 7D were analyzed using the same curve fitting method described in the previous experiments. A paired t-test between the PSEs of the test and control arrays again revealed no significant difference in perceived size ($t(4) = 1.93, ns$).

The Binding Ring Illusion was not observed in either of the partial binding ring configurations tested here. As such, we can conclude that processing of the preserved local features does not underlie the illusion. Alternatively, these results suggest that mechanisms within a higher, more global stage of processing may underlie the illusion.

Experiment 4: perceived size of test and reference arrays with lines only present either within the interior of the elements or connecting the elements

1 Data File

<http://dx.doi.org/10.6084/m9.figshare.157060>

General discussion

In this manuscript we introduced a new size illusion that we call the Binding Ring Illusion. The Binding Ring Illusion is a variant of the Delboeuf and Ebbinghaus Illusions and demonstrates that

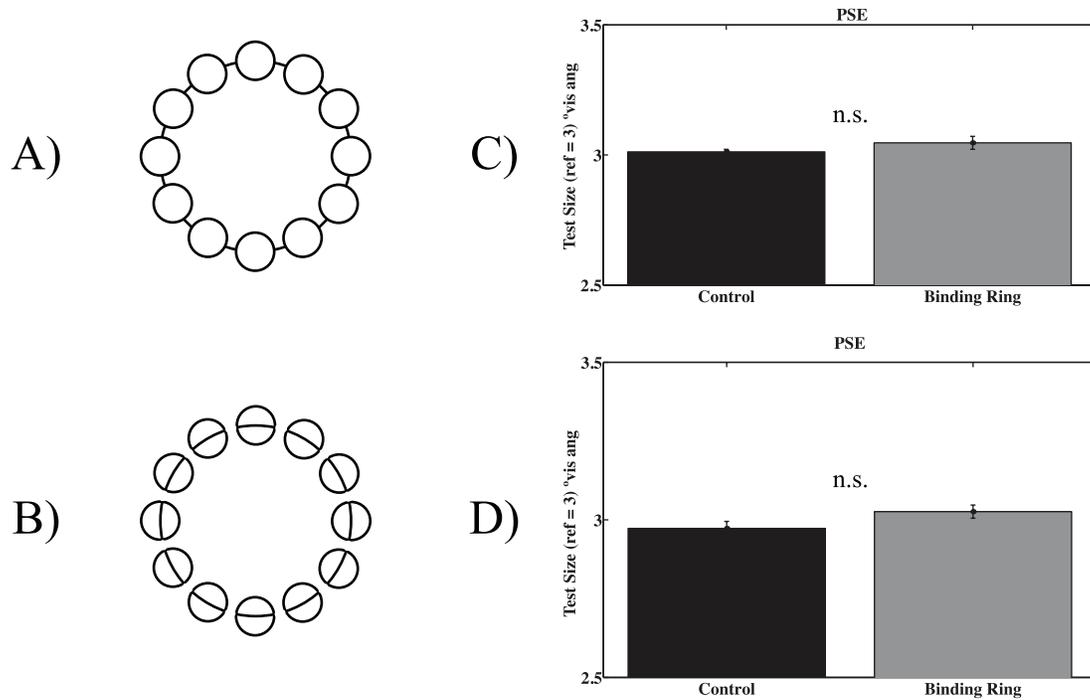


Figure 7. Configurably altered binding ring stimuli. **A)** The test stimulus used in experiment 4a. **B)** The test stimulus used in experiment 4b. **C)** The results of experiment 4a. **D)** The results of experiment 4b. There was no significant difference (n.s.) in perceived size between the control and binding ring tests in either condition.

the perceived size of an array is subject to effects of assimilation. Specifically, the perceived size of a circular array of elements is underestimated when a ‘binding ring’ is superimposed on the array. The purpose of the above experiments was to demonstrate that the illusion can be quantified, to investigate possible explanations for its occurrence and to begin to characterize the stimulus factors that lead to misperceived size.

A number of observations can be made based on the results of these experiments. Firstly, the Binding Ring Illusion can indeed be quantified. Using both methods of constant stimuli and adaptive staircases we were able to measure significant differences in the perceived size of an array as a function of the presence and size of a binding ring. Secondly, the size of the binding ring significantly influences the magnitude of the illusion (experiment 2). Specifically, in order to produce the greatest effect, the binding ring has to superimpose the array and furthermore, as the size of the superimposed ring decreases, the magnitude of the illusion increases. These findings are consistent with existing assimilation theories of similar size illusions such as the Delboeuf and Ebbinghaus illusions^{9,10,15,17}. In addition, the perceived size of the array was slightly *increased* only when the binding ring was large enough to completely encompass the array. This suggests that the outer radius of the array serves as the reference point for the assimilation process. It has been argued that assimilation is largely influenced by the perceived unification of the components as a single object^{17,29}. This is consistent with our results such that the strongest assimilation effects occurred when the circle was superimposed on the array and could be easily perceived as a unified figure. In these conditions we observe a significantly larger magnitude of size illusion than when the binding ring was not superimposed on the array.

The Delboeuf and Ebbinghaus Illusions both demonstrate that the perceived size of an interior object can be influenced by the presence of a surrounding stimulus. The Binding Ring Illusion, on the other hand, provides a complimentary observation that the perceived size of a surrounding stimulus can be influenced by the presence of an interior stimulus. Indeed, the smallest binding ring condition in experiment 2 is an identical configuration to that commonly used to demonstrate the Ebbinghaus illusion.

Secondly, the magnitude of the illusion is greater when the stimuli are low- compared to high-pass filtered (experiment 3). However, in both cases the magnitude of the illusion is comparable if not greater than that observed with full spectrum stimuli. As such, we can conclude that: either processes within distinct spatial frequency channels can independently lead to the illusion, or the illusion is mediated by mechanisms at a later stage of processing that follows the integration of high- and low-spatial frequencies. In the latter case, one may conjecture that the initial LSF bias is attenuated once spatial frequency information has been integrated in object recognition areas such as those located in the inferotemporal cortex (IT)³⁰. This stands in contrast to several recent findings using functional and structural MRI that have implicated visual areas as early as V1 as playing a key role in the representation of perceived size^{31–33}. Given the classical receptive field properties of V1 neurons, it is likely that these observations arise due to feedback to V1 from higher visual areas, that in the case of the Binding Ring Illusion may contain integrated representations of spatial frequency. This is in line with recent research on the Müller-Lyer Illusion using dynamic causal modelling³⁴. It was demonstrated that illusion strength could be predicted by modulating bilateral connections between the lateral

occipital cortex (LOC) and right superior parietal cortex (SPC). The model suggests that LOC is involved in size scaling to generate size invariant object representations that are further processed in SPC and relayed back to V1 to generate conscious illusory percepts.

One hypothesis for why the illusion is greater in the LSF condition is that due to blur, the individual array elements in the LSF condition are perceptually larger than the HSF and full-spectrum conditions. Because the elements appear larger, the perceived distance between the outer radius of the array and the binding ring is increased. The results of experiment 2 suggest that this may lead to an increased assimilation effect. Alternatively, the blurring of the image increases the thickness of the binding ring and it could be the case that this increases its effect on the perceived size of the array. Further research will be necessary to fully determine why the blurred stimulus increased the magnitude of the illusion.

Thirdly, the illusion does not manifest when only the local configural features of the binding ring are present. This was true even when the binding ring only connects the array elements (experiment 4a). This result is intriguing because past work has demonstrated that elements that are perceptually grouped into a common object will be perceived to be closer together than those that are not. Specifically, if a series of dots are arranged to form a dotted contour, the distance between any two adjacent dots will be perceived as being shorter than the distance between any one of them and another equally-distanced dot that does not lie along the contour³⁵. One possible extension of this observation is that an object formed out of the grouping of individual elements may appear smaller on the basis of the elements appearing closer together. Based on this assumption we thought it possible that the partial binding ring of experiment 4a may serve as an additional cue that the individual elements belong to a common object and therefore lead to it appearing smaller. The configuration of experiment 4a explicitly links the elements of the array; however, this does not lead to the illusory reduction in perceived size. This may be explained by the observed effects of the Opperl-Kundt Illusion^{20,21} that demonstrates that the distance between two points is overestimated when it is filled with a number of tick marks compared to two equally spaced points of an undivided extent; however, as the density of these divisions increases, the effect diminishes³⁶. Therefore,

connecting the interior elements should lead to a more veridical perception as observed here. As such, it is unlikely that the Binding Ring Illusion arises due to a misperception of the perceived distance between array elements.

Conclusion

Although we readily perceive a circular array of elements as a circle, there are many possible alternate perceptions that could be formed. For example, the circles could be grouped into pairs symmetrical about the vertical axis, or perceived as ellipses arranged in an elliptical array that is receding in depth. That we perceive such a stimulus as a circle reflects the constructive processes that are embodied in the functional and structural architecture of the visual system. Importantly, the circle that we perceive does not explicitly exist in the retinal image and must therefore be constructed. As such, the size of the circle that we perceive must be itself constructed as well. The Binding Ring Illusion demonstrates that this constructive process includes the assimilation of other co-occurring stimuli, particularly those that spatially overlap the array.

Author contributions

Dan McCarthy contributed to the theoretical foundation, experimental design, data analysis and writing of the manuscript. Colin Kupitz contributed to the experimental design, implementation, data collection, data analysis and writing of the manuscript. Gideon Caplovitz contributed to the theoretical foundation, experimental design and writing of the manuscript.

Competing interests

No competing interests were disclosed.

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The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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Current Referee Status:

Referee Responses for Version 2



Dejan Todorović

Laboratory of Experimental Psychology, Department of Psychology, University of Belgrade, Belgrade, Serbia

Approved: 23 January 2014

Referee Report: 23 January 2014

The authors have taken into account my comments in the revised text. I have no further comments.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Competing Interests: No competing interests were disclosed.



Ming Meng

Department of Psychological Brain Sciences, Dartmouth College, Hanover, NH, USA

Approved: 21 January 2014

Referee Report: 21 January 2014

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Competing Interests: No competing interests were disclosed.



Simone Gori

Developmental and Cognitive Neuroscience Lab, Department of General Psychology, University of Padua, Padua, Italy

Approved: 20 January 2014

Referee Report: 20 January 2014

I approve this version, I think this paper was already interesting in its first version and I believe the Authors did improve it even further in this new version.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Competing Interests: No competing interests were disclosed.

Referee Responses for Version 1



Simone Gori

Developmental and Cognitive Neuroscience Lab, Department of General Psychology, University of Padua, Padua, Italy

Approved: 03 April 2013

Referee Report: 03 April 2013

The presented manuscript is very interesting and well written. The experiments are very well conducted and it is a pleasure to read. The authors introduce a new size illusion and they investigate it using a very good methodology, providing clear results. I have some suggestions that in my opinion could improve the manuscript even more, but my general opinion is extremely positive.

Please see my suggestions below:

1. The introduction is really short, and it doesn't cover the topic of size illusion properly. Several other interesting examples of size illusions should be cited and discussed to provide a better understanding of the topic. Firstly, I would suggest discussing the literature on the illusions that are cited by the authors which are very similar to the one that they introduced here. For example, several interesting papers have been produced on The Ebbinghaus Illusion (which should maybe be called the Ebbinghaus-Titchener illusion, referring also to the 1902 Titchener book that made it popular) that maybe should be discussed (just few examples, without pretending to be complete at all: Roberts *et al.* 2005; Nemati, 2009; Doherty *et al.*, 2010; Schwarzkopf and Rees, 2013). The same can be said for the related Delboeuf illusion, which is suggested to be caused by the same brain mechanisms by Roberts *et al.* (2005). A few examples of recent works that may be worth checking are: Zanuttini and Daneyko (2010); Jaeger and Long (2007). Moreover, other interesting size illusions could be mentioned in the introduction, for example: The Muller-Lyer Illusion (Zeman *et al.* 2013; Plewan *et al.* 2012; Proulx and Green, 2011), the Oppel-Kundt Illusion (Wackermann, 2012a,b; Savazzi *et al.*, 2012) and the related filled area illusion (Giora and Gori, 2011); the Breathing Light Illusion (Gori and Stubbs, 2006; Anstis *et al.* 2007; Gori *et al.* 2010), StarTrek Illusion (Qian and Petrov, 2012), Accordion Grating Illusion (Gori *et al.*, 2011; 2013; Yazdanbakhsh and Gori, 2011) and the Fat Face Illusion (Thompson and Wilson, 2012; Sun *et al.* 2012), to name just a few.

2. Moreover, it would be nice if the authors could explain in more detail why studying this new illusion is relevant. In other words I would like to know which characteristics separate this new configuration from the ones already known.

3. In the introduction of Experiment 3, it should be noted that the filled area illusion (Giora and Gori, 2010) is influenced by spatial frequency and a similar procedure to the one used in this study was employed. As both are size illusions, it would be interesting to discuss the similarities between the two.

4. When the authors state that several illusions are based on local configuration features, as well as citing the 1860's work, they should also cite some new literature to provide more up to date references.

5. In the discussion, the difference between perceiving a difference and perceiving a group (Gori and Spillmann, 2010) could be interesting to discuss in relation to the last experiment.
6. The link with the Oppel-Kundt Illusion could be discussed in more detail, for example, by also referring to the work done by Wackermann.
7. In the discussion, some references to the potential brain mechanisms involved would be the icing on the cake in my opinion. Visual illusions are open windows on how the brain works and they are interesting tools to investigate it in a non-invasive manner. It would be nice to read about the hypothetical brain mechanisms underlying specific illusions.

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I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Competing Interests: No competing interests were disclosed.



Dejan Todorović

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Approved: 21 March 2013

Referee Report: 21 March 2013

This paper is a study of a size perception illusion related to the Ebbinghaus illusion and the Delboeuf illusion. The study includes quantification of the basic phenomenon and some relevant parameters. It is well designed and executed, and contributes to our knowledge of this class of illusions. Size illusions of

this class have been known for a long time and are still lacking a generally accepted explanation, but have not been studied much in recent years.

My only substantial criticism concerns the authors' suggestion that the effect they studied is based on a high-level mechanism, late in the processing stream. I don't find that they have offered enough evidence for such a conclusion. Note that recent research on the Ebbinghaus illusion ([Schwarzkopf et al 2010, *Nature Neuroscience*, 14\(1\), 28-30](#)), not cited by the authors, indicated that the strength of the illusion correlates with the size of V1, suggesting contributions to the illusion fairly early in the visual stream.

As a minor comment, it is commendable that the authors have cited the early research on size illusions, but some of the references, although often cited in that form in the recent literature, are in fact incorrect. For example, Opper did not publish about the the illusion named after him in 1854/55 but in 1860/61, and in that paper he did not report about the dependence of the illusion on the number of tickmarks. For more details, see [Wackermann J. & Kastner K. \(2010\), *Acta Neurobiol Exp*, 70: 423-434](#). Also, Ebbinghaus did not publish the illusion named after him in the reference cited in the paper, and in fact seems to have never published it. For details, see [Burton, G. \(2001\), *History of Psychology*, 4, 228-244](#).

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Competing Interests: No competing interests were disclosed.



Ming Meng

Department of Psychological Brain Sciences, Dartmouth College, Hanover, NH, USA

Approved: 18 March 2013

Referee Report: 18 March 2013

The current paper presents a novel variant of visual size illusion that is named the Binding Ring Illusion by the authors. The illusory effect is quite strong as one could easily experience the illusion him/herself by looking at figure 2. The authors further tested several stimulus conditions to investigate why the Binding Ring Illusion occurs. Their results suggest that size assimilation at a relatively high level in the visual processing stream may underlie the illusion. I think this is a clearly written paper, the results are clear-cut, and the conclusion of this paper is well supported by the results.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Competing Interests: No competing interests were disclosed.
