Dynamic illusory size contrast: A relative-size illusion modulated by stimulus motion and eye movements

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We present a novel size-contrast illusion that depends on the dynamic nature of the stimulus. In the dynamic illusory size-contrast (DISC) effect, the viewer perceives the size of a target bar to be shrinking when it is surrounded by an expanding box and when there are additional dynamic cues such as eye movements, changes in retinal eccentricity of the bar, or changes in the spatial position of the bar. Importantly, the expanding box was necessary but not sufficient to obtain an illusory percept, distinguishing the DISC effect from other size-contrast illusions. We propose that the visual system is weighting the different sources of information that contribute to size perception based on the level of uncertainty in the retinal image size of the object. Whereas the growing box normally has a weak influence on the perceived size of the target bar, this influence is enhanced when other dynamic changes in the environment (e.g., eye movements, changes in retinal eccentricity, and target motion) lead to uncertainty in the retinal size of the target bar. Given the compelling nature of the DISC effect and the inherently dynamic nature of our environment, these factors are likely to play an important role in everyday size judgments.

Introduction

Having accurate perceptual representations of object size is crucial for interacting with the world around us. However, an object's size is not inherently represented in the size of its projected retinal image. Rather, the perceived size of an object is constructed by integrating multiple sources of information including, but not limited to, retinal image size, physical and perceived distance (Berryhill, Fendrich, & Olson, 2009; Boring, 1940; Emmert, 1881; Ponzo, 1911), an object's geometrical and textural properties (Giora & Gori, 2010; Kundt, 1863; Lotze, 1852; Oppel, 1855; Helmholtz, 1867; Westheimer, 2008), knowledge of an object's typical size (Konkle & Oliva, 2012), and the relative size of different objects in a scene (Coren & Girgus, 1978; Roberts, Harris, & Yates, 2005; Robinson, 1972). The roles these different sources of information play in the construction of perceived size can be revealed through a number of illusions in which the size of an object is misperceived. For example, classical size-contrast and size-assimilation illusions such as the Ebbinghaus illusion (Burton, 2001; Thiéry, 1896) or the Delboeuf illusion (Delboeuf, 1892) demonstrate that the size of a surrounding context can influence the perceived size of a central object (Figure 1). More recently described illusions, such as the "binding ring illusion" (McCarthy, Kupitz, & Caplovitz, 2013), the "StarTrek illusion" (Qian & Petrov, 2012), the "shrinking building illusion" (Fukuda & Seno, 2011), and the "breathing light illusion" (Anstis, Gori, & Wehrhahn, 2007; Gori, Giora, & Agostini, 2010; Gori & Stubbs, 2006), further demonstrate that the perceived size of an object is influenced by the context in which it is viewed. Together, these illusions have provided insights into our understanding of how we perceive the size of an object. Additionally, understanding such illusions may have practical implications, such as the potential effects of plate size on food consumption (van Ittersum & Wansink, 2012) and the effects of striped clothing on bodily appearance (Ashida, Kuraguchi, & Miyoshi, 2013; Thompson & Mikellidou, 2011). In this paper, we introduce a novel size illusion that highlights the role of

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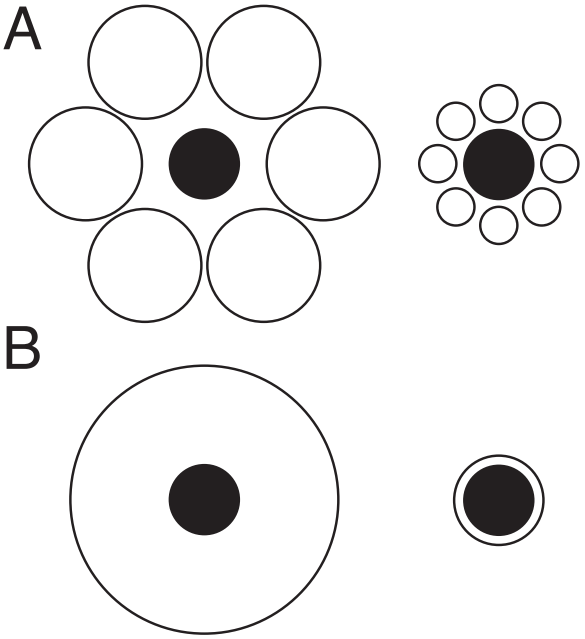
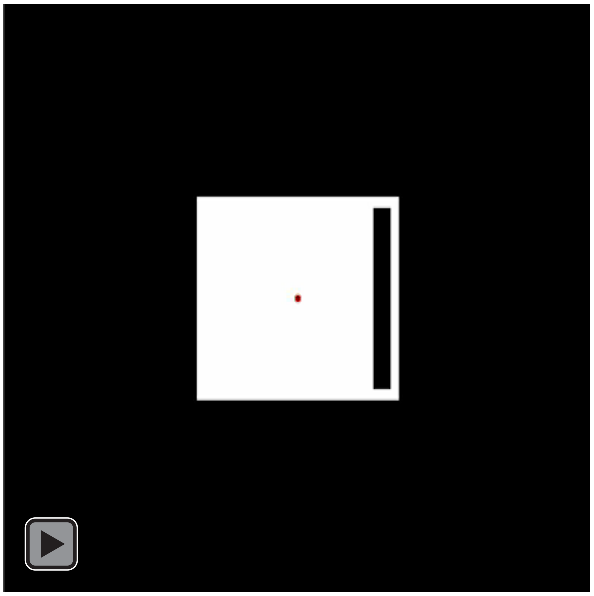


Figure 1. Classic size-contrast illusions. In the Ebbinghaus (A) and Delboeuf (B) illusions, the inner filled circle is perceived to be larger on the right and smaller on the left. In fact, all filled circles are the same physical size.



Movie 1: Full Oblique condition. Note that the black target bar appears to shrink and expand as the surrounding box expands and shrinks. Click on the image to view the movie. Movies are best viewed in looped mode.

visual motion in modulating the contribution of different sources of information in determining the perceived size of an object.

One of us (R. E. B. M.) first noticed the illusion while watching videos with his children using Apple's QuickTime (v10.1, Apple Inc., Cupertino, CA). In QuickTime, the playback controls are contained within a black bar that is positioned at the center-bottom of the video window by default. When transitioning from "windowed" mode to "full-screen" mode, the video dynamically expands to fill the monitor. At the same time, the position of the control bar changes, but the physical size of the control bar does not. However, the perceived size of the control bar changes dramatically, appearing to shrink when going to full-screen mode and to grow when going back to windowed mode. As the magnitude of the illusion primarily depends upon the dynamic change in the relative size of the target bar and the surrounding background, we have termed the effect "dynamic illusory size contrast" (DISC). In comparison to other illusions of size contrast (e.g., the Ebbinghaus and Delboeuf illusions, Figure 1), the DISC effect is strikingly compelling. It may be that this arises because, unlike other classic size-contrast illusions that are static in nature, the size of the target bar in the DISC stimulus is perceived to continuously change in a smooth fashion.

In order to explore this illusion in a more controlled fashion, we created a simplified version with a surrounding context (a solid white box), a central target object (a black rectangle), and a fixation point. Readers can experience the DISC stimulus for themselves by viewing Movie 1. Note that although the size of the black bar appears to shrink as the surrounding box grows and to grow as the surrounding box shrinks, it is not changing. We think readers will find that the perceived change in size in the DISC effect is greater than one may experience by simply comparing two still images depicting the smallest and largest box sizes of the video sequence (Figure 2).

What is it about this dynamic display that leads to such a robust change in the perceived size of the inner bar? We identified four potential factors that could contribute to the DISC effect: (a) the relative size change between surrounding box and target bar; (b) the change in real-world position of the target bar; (c) the change in retinal eccentricity of the target bar; and (d) the execution of a smooth pursuit and/or saccadic eye movements. In the following set of experiments, we systematically explore the contributions that each of these factors make to the magnitude of the DISC effect. Our results demonstrate that the contribution of relative size carries more weight in a dynamic environment in which both the target bar and contextual surround are physically moving or are perceived to be moving. In our interpretation of these results we raise the hypothesis that the dynamic nature of the stimulus leads to greater uncertainty about the retinal size of the target object. As a result, other sources of information (i.e., relative size) contribute more to its perceived size, thereby increasing the magnitude of the illusory percept.

Figure 2. Static frames depicting the smallest (left) and largest (right) box sizes of the video sequence in Movie 1. We invite readers to compare the size of the black bar in both frames, which are physically identical, and to then compare the subjective magnitude of this illusory effect with that perceived from the DISC stimulus in Movie 1.

Methods

Participants

Observers in each experiment consisted of student volunteers participating in exchange for course credit from the University of Nevada, Reno. Fifteen participants completed Experiment 1; 11 participants completed Experiment 2; and 11 participants, seven of whom also completed Experiment 2, completed Experiment 3. Prior to participating, each observer provided informed consent according to the guidelines of the Department of Psychology and the Institutional Review Board of the University of Nevada, Reno. The research protocol of all experiments adhered to the tenets of the Declaration of Helsinki. All participants reported normal or corrected-to-normal vision and were naive to the specific aims and designs of the experiments.

Data from five additional participants were excluded due to the participants' mix-up in the response buttons, extreme response bias, or high variability of responses for the same trial parameters leading to poor psychometric curve fitting.

Apparatus and display

Stimuli were presented on a ViewSonic Graphic Series G220fb monitor (20-in., 1024 × 768 pixel resolution, ViewSonic Corporation, Walnut, CA) with an 85-Hz refresh rate. The stimulus computer was a 2.5-GHz Mac Mini (Apple Inc., Cupertino, CA) with an Intel HD Graphics 4000 768 MB graphics processor (16 GB of DDR3 SDRAM). Stimuli were created and presented with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) for MATLAB (version 2012b, Mathworks Inc., Natick, MA). The stimuli consisted of a black (0.44 cd/m^2) target bar, a black (0.44 cd/m^2) and red (18.94 cd/m^2) fixation spot, and a white (100.20 cd/m^2) surrounding box presented on a black (0.44 cd/m^2) background. Participants viewed the stimuli binocularly from a distance of 73 cm with their chin positioned in a chin-rest. Eye movements were not monitored.

Trial overview

Here, we outline the general trial structure for all experiments. The specific details of each trial type are outlined below. The general trial structure for one condition is outlined in Figure 3A. A summary of the dynamic components that are included in each condition is shown in Table 1. We also provide video versions of all our stimuli so that the readers may experience the reported effects for themselves, although it should be noted that the stimuli used in the experiments consisted only of the first half of each "loop-able" movie demo.

Every trial was initiated with the presentation of a fixation spot that consisted of an inner black circle (0.1° radius) enclosed by an outer red circle (0.2° radius). After this 500-ms fixation period, participants were shown a static stimulus consisting of a fixation spot and a vertically oriented target bar (~3.2° height × 0.5° width) positioned within the borders of a surrounding

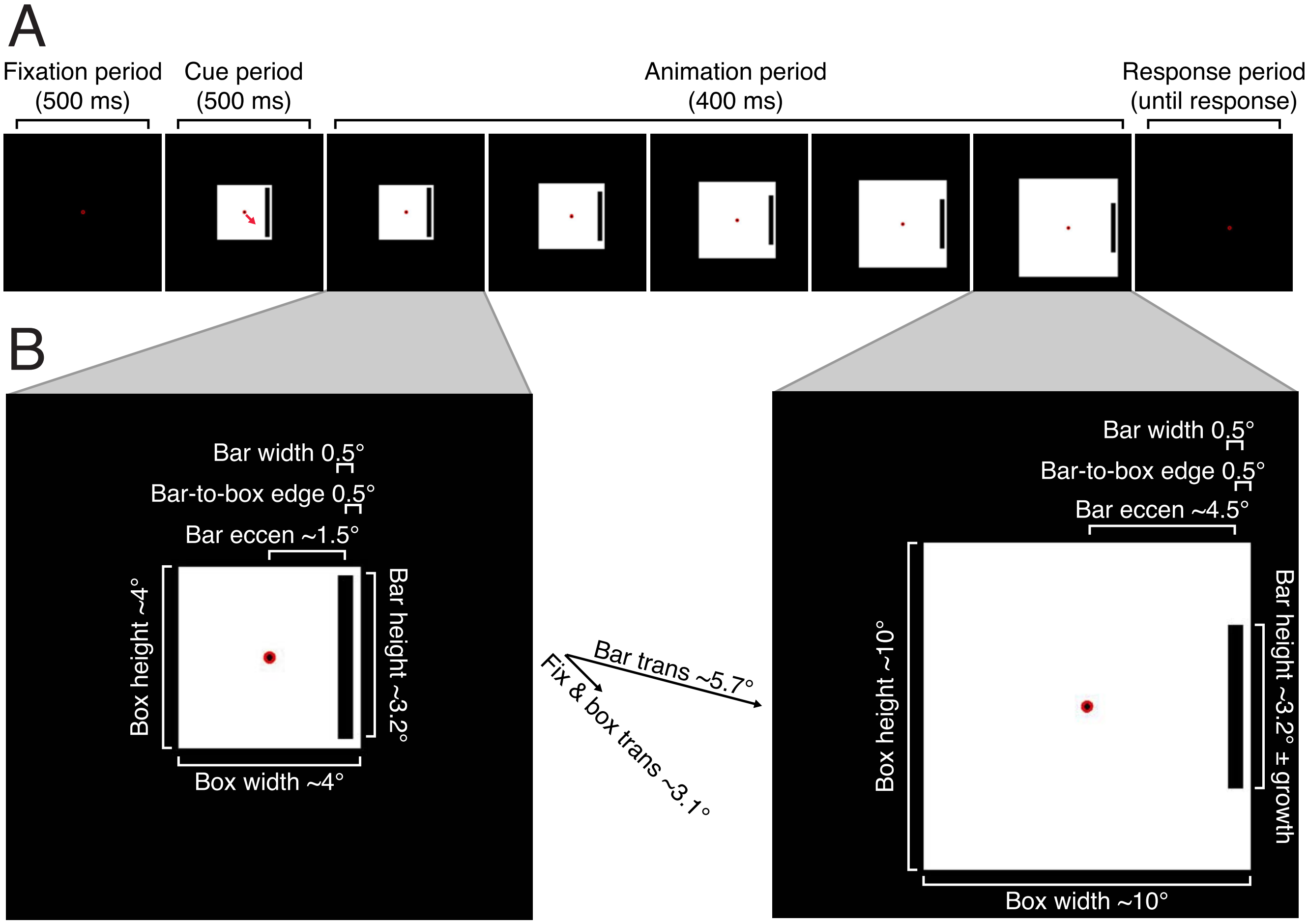
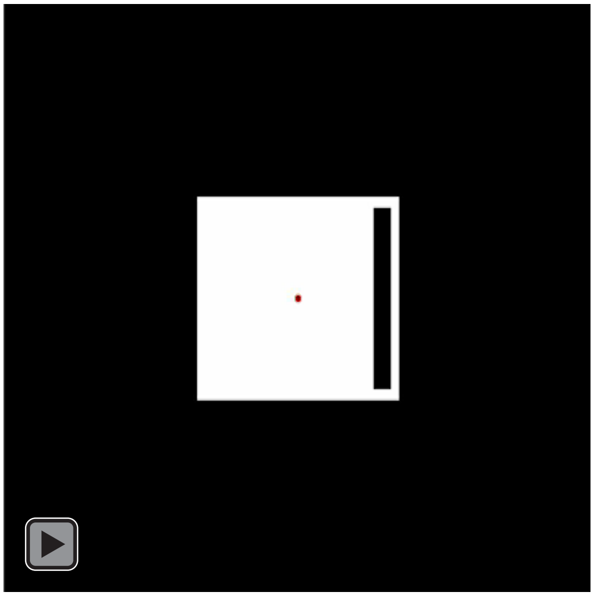


Figure 3. An outline of the Full Oblique condition. (A) The timeline of events for a single trial from the Full Oblique condition. A video of this condition is shown in Movie 1, although readers should note that the actual trials consisted only of the first half of each "loopable" movie demo. (B) The initial (left) and final (right) stimulus configuration of the animation period. All conditions started from the same initial configuration, except the Rigid Box condition of Experiment 2.

white box (~4° for all but one condition; ~10° for the Rigid Box condition of Experiment 2). The fixation spot was centered within the surrounding box and the target bar was vertically centered 1.5° to the right of fixation and 0.5° from the right edge of the box. On trials in which the fixation spot translated and the subject was required to smoothly pursue the fixation spot, an arrow indicated the impending direction of motion. On trials with no translation of the fixation spot, a circle cue appeared around the fixation. The stimulus remained static for the 500-ms cue period and then smoothly changed over a 400-ms animation period. The particular dynamic changes to the stimuli were specific to each experimental condition (see

Condition label	Experiment	Expanding box	Bar motion	Increasing eccentricity	Eye movements	Movie demo
Full Oblique	1, 2, 3	+	+	+	+	Movie 1
Full Horizontal	1	+	+	+	+	Movie 2
Stationary Bar	1	+	–	+	+	Movie 3
Full Opposing Horizontal	1	+	+	+	+	Movie 4
Fixed Eyes	1	+	+	+	–	Movie 5
Pure Size-Contrast	1	+	–	–	–	Movie 6
Constant Eccentricity	2	+	+	–	+	Movie 7
Rigid Box	2	–	+	+	+	Movie 8
Static Frames	3	+	+	+	+	Movie 9

Table 1. All experimental condition labels and their associated movie demo. *Note*: A + or – indicates the presence or absence of a given dynamic component, respectively.



Movie 2: Full Horizontal condition. All translations were constrained to the horizontal meridian. Click on the image to view the movie. Movies are best viewed in looped mode.

below), but included one or more of the following: a uniform increase in the size of the surrounding white box from ~ 4° to ~ 10°, a translation of the surrounding box, a translation of the fixation spot, a translation of the target bar, and an increase or decrease in the vertical extent of the target bar. On trials in which the surrounding box expanded, it increased in size from ~4° to ~10° over the 400-ms animation period (i.e., each edge of the box expanded outward at a rate of ~7.6°/s). On all trials, the bar remained vertically centered at a fixed distance of 0.5° from the right edge of the box throughout the trial. After the 400-ms animation period, the stimulus, except for the fixation spot, was removed and participants reported whether the target bar had increased or decreased in length by pressing one of two buttons on a keyboard. Participants were instructed to maintain fixation on the fixation spot at all times and covertly attend to the size of the target bar. No feedback was provided to the participants.

The experiments used a nulling technique in which the physical change in target bar length during the animation phase was adjusted from trial-to-trial to minimize the participant's perceived change in size. The decision to use a nulling technique was based on our past experience of successfully applying it to quantify other dynamic illusions (e.g., Caplovitz, Paymer, & Tse, 2008; Caplovitz & Tse, 2007). On each trial, the physical change in target bar length was selected from one of 18 growth rates spanning a range of ~±77%, with equal spacing between rates, using an adaptive staircase procedure. Negative growth rates indicate that the bar was contracting and positive growth rates indicate that the bar was expanding. Thus, in the most extreme conditions of the staircase, the length of the target bar would be either 77% longer or 77% shorter at the end of the animation than at the beginning. Each condition in each experiment used six pseudorandomly interleaved staircases, with half starting from the minimum growth rate and half starting from the maximum growth rate (four staircases were used for two participants in Experiment 1). Each staircase lasted for a total 25 trials. For each staircase, the growth rate on subsequent trials was adjusted depending on the participant's response. If the participant indicated that the bar appeared to have shrunk, then the next trial in the same staircase would use the next highest growth rate (always moving one step at a time), and vice versa.

To minimize the influence of environmental cues (e.g., the edge of the monitor), the starting position of the entire stimulus was randomly varied by up to ±1° horizontally and vertically from the center of the screen. To avoid participants developing a template of the initial size of the box and bar, each varied independently by up to 2% from trial to trial.

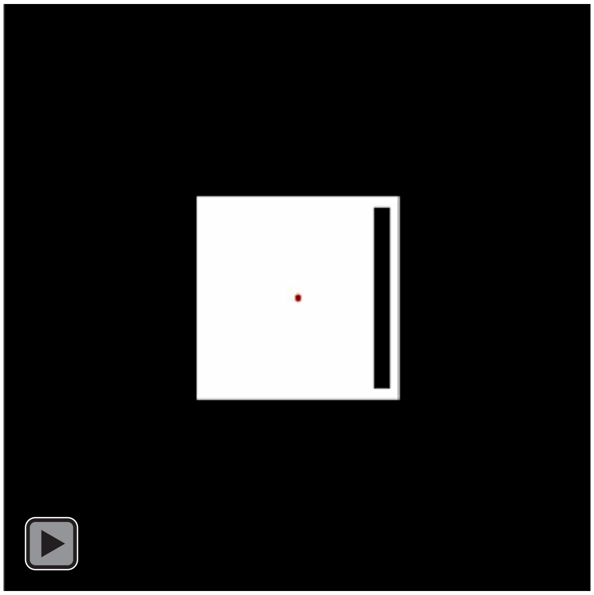
Experiment 1

In Experiment 1 we sought to reproduce our original observation with a controlled stimulus. In addition, we tested whether changes in real-world position of the bar and the execution of a smooth pursuit and/or saccadic eye movements modulate the magnitude of the DISC effect.

Experiment 1 contained six distinct conditions (Table 1). The six conditions differed in their dynamic component, although the retinal stimulation was largely matched across conditions (excluding the Pure Size-Contrast condition, see below) for a given growth rate of the bar.

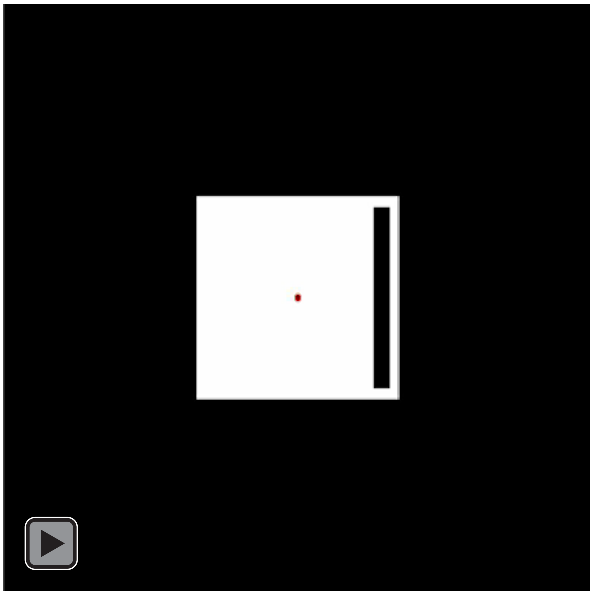
Figure 3 and Movie 1 depict the simplified version of our original observation. As this stimulus contains all dynamic components with movement vectors at an oblique angle, we refer to it as the Full Oblique condition. As can be seen in Movie 1, the fixation spot maintained its position at the center of the surrounding box, which translated down and to the right as it expanded in size. Specifically, in this condition, the center of the box and the fixation spot translated at an oblique angle 45° down and to the right over a distance of ~3.1° (4.4° for two participants), corresponding to a speed of ~7.6°/s (11.1°/s for two participants). The target bar translated at a 22.5° angle (26.6° for two participants) down and to the right over a distance of ~5.7° (7.0° for two participants), corresponding to a speed of ~14°/s (17.5°/s for two participants).

The Full Horizontal condition (Movie 2) was similar to the Full Oblique condition in that it contained all the dynamic components described above, but all transla-



Movie 3: Stationary Bar condition. The physical position of the target bar does not change. Click on the image to view the movie. Movies are best viewed in looped mode.

tions were constrained to the horizontal meridian. In this condition, the surrounding box translated horizontally as it expanded in size. The fixation spot and the target bar translated to the right, such that the fixation spot maintained its centered position and the target bar maintained its position along the right edge of the surrounding box. As in the Full Oblique condition, the center of the box and the fixation spot translated a distance of ~3.1°, corresponding to a speed of ~7.6°/s. To maintain its position relative to the surrounding box, the target bar translated to the right over a distance of ~6.2°, corresponding to a speed of ~15.2°/s.



Movie 4: Full Opposing Horizontal condition. The fixation spot translates away from the target bar. Click on the image to view the movie. Movies are best viewed in looped mode.

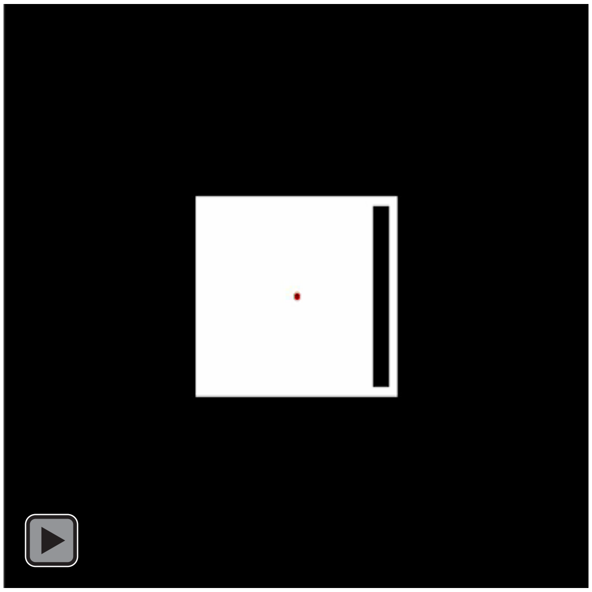
In the Stationary Bar condition (Movie 3), the physical position of the target bar on the screen did not change over the course of the animation. In this condition, the surrounding box translated to the left as it expanded in size. The fixation spot also translated to the left to maintain its central position relative to the surrounding box. The center of the box and the fixation spot translated over a distance of ~3.1°, corresponding to a speed of ~7.6°/s. These values were chosen so that the stationary target bar maintained its position along the right edge of the surrounding box throughout the trial.

Unlike the Full Horizontal condition, the fixation spot translated away from the bar in the Stationary Bar condition. To verify that this change did not account for potential differences in the magnitude of the illusion between these conditions, we included a Full Opposing Horizontal condition as a control (Movie 4). This control condition contained all four dynamic components, as in the Full Horizontal Condition, but the fixation spot translated away from the bar, as in the Stationary Bar condition. In this control condition, the fixation spot maintained its central position relative to the surrounding box as both translated to the left, while the surrounding box expanded in size. Each translated over a distance of ~1.5°, corresponding to a speed of ~3.8°/s. In order to maintain its position along the right edge of the surrounding box, the target bar translated to the right covering a distance of ~1.5°, corresponding to a speed of ~3.8°/s.

The Fixed Eyes condition (Movie 5) did not contain any smooth pursuit eye movement and the fixation spot remained stationary throughout the trial. In this condition, the surrounding box did not translate, although it still expanded in size. To maintain its relative position to the right edge of the expanding box, the black bar translated to the right over a distance of ~3.1°, corresponding to a speed of ~7.6°/s.

The only dynamic change in the Pure Size-Contrast condition (Movie 6) was the relative size change between the surrounding box and the target bar. In this condition, the center of the expanding surrounding box translated to the left over a distance of ~3.1°, corresponding to a speed of at 7.6°/s. The fixation spot and the target bar remained stationary.

Thirteen participants completed 150 trials for each condition, except the Pure Size-Contrast condition, for a total of 750 trials in a single session (5 conditions × 6 interleaved staircases/condition × 25 trials/staircase). Six of these same participants completed an additional 150 trials (6 interleaved staircases × 25 trials/staircase) of the Pure Size-Contrast condition in a separate session. Two participants completed 100 trials for each condition, except the Pure Size-Contrast, for a total of

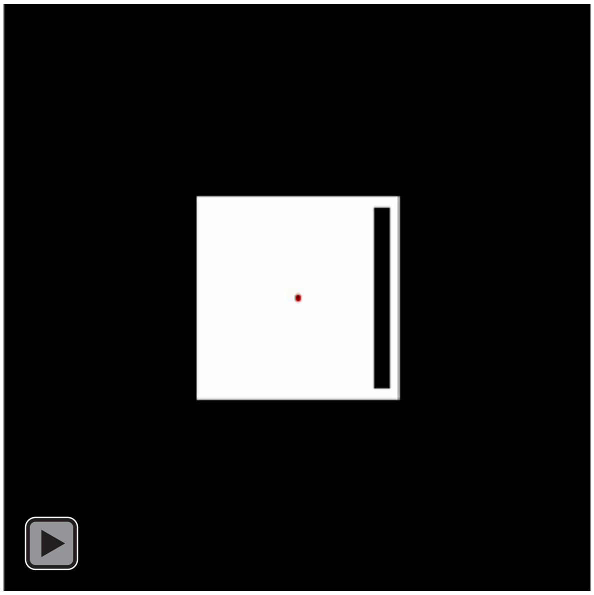


Movie 5: Fixed Eyes condition. The fixation spot remains stationary. Click on the image to view the movie. Movies are best viewed in looped mode.

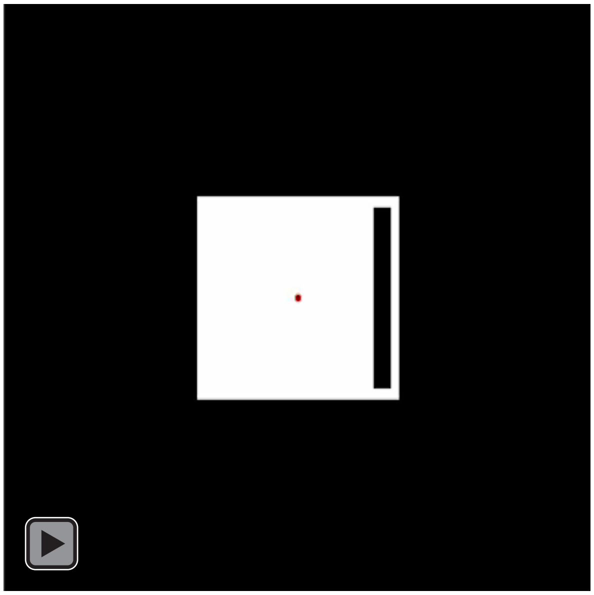
500 trials in a single session (5 conditions × 4 interleaved staircases/condition × 25 trials/staircase).

Experiment 2

Experiment 2 was designed to further investigate the factors that influence the DISC effect. Specifically, this experiment tested whether the DISC effect is modulated by changes in target eccentricity as the bar moves across the screen and the degree to which it depends on the dynamic change in the size of the surrounding box.



Movie 6: Pure Size-Contrast condition. The only dynamic change is the relative size change between the surrounding box and the target bar. Click on the image to view the movie. Movies are best viewed in looped mode.

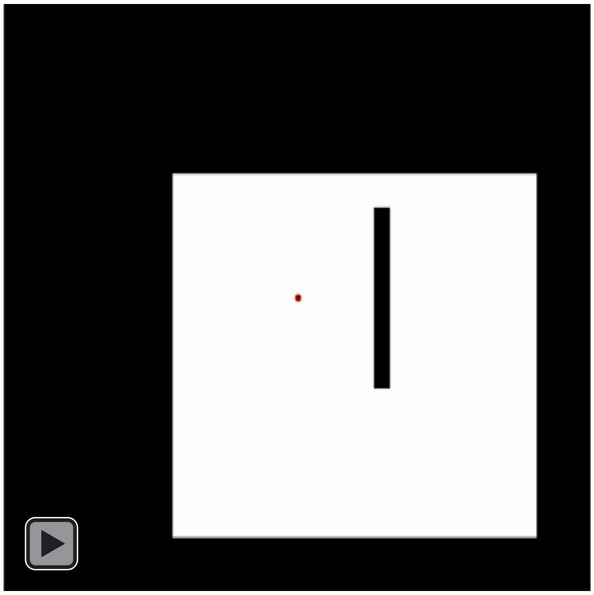


Movie 7: Constant Eccentricity condition. The distance between the target bar and fixation point does not change. Click on the image to view the movie. Movies are best viewed in looped mode.

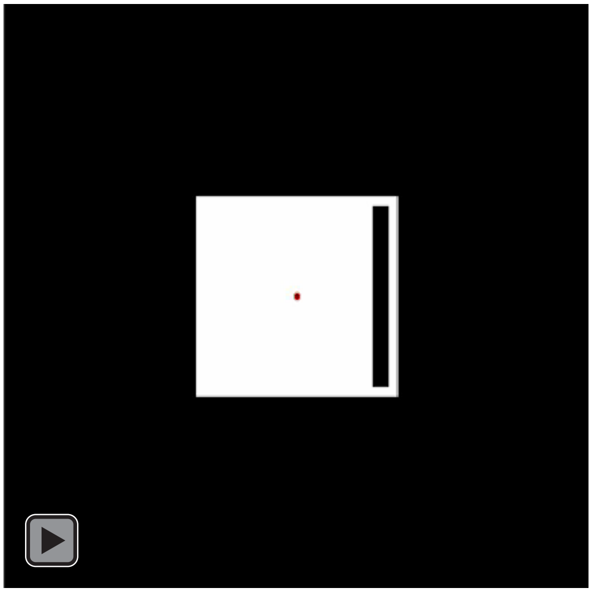
Experiment 2 contained three conditions (Table 1). The first condition was a replication of the Full Oblique condition (Figure 3 and Movie 1), which led to the largest illusory effect in Experiment 1. The remaining conditions (described below) tested the contribution of target eccentricity and the size change of the surrounding box, respectively, by removing each of these dynamic components from the full stimulus. The eye movement necessary to maintain gaze on the fixation spot was matched across the three conditions.

The Constant Eccentricity condition (Movie 7) shared all dynamic components with the Full Oblique condition except that the eccentricity of the target bar did not increase over the course of the trial. In this condition, the surrounding box translated at an oblique angle of 67.5° down and to the left over a distance of 2.3°, corresponding to a speed of 5.8°/s. The fixation spot and target bar translated together at an oblique angle of 45° down and to the right over a distance of 3.1°, corresponding to a speed of 7.6°/s, thereby maintaining their positions relative to the right edge of the surrounding box.

The Rigid Box condition (Movie 8) was identical to the Full Oblique condition, except that the surrounding box started off large, and remained unchanging in a position that matched the final configuration of the Full Oblique condition. In other words, the large box remained rigid while the fixation spot and the black target bar translated together down and to the right.



Movie 8: Rigid Box condition. There is no relative size change between the surrounding box and the target bar. Click on the image to view the movie. Movies are best viewed in looped mode.



Movie 9: Static Frames condition. The dynamic phase consists only of a moving fixation point, without the surrounding box and the target bar. Click on the image to view the movie. Movies are best viewed in looped mode.

Specifically, the box (10.1° sides) was stationary throughout the trial in a position such that the final location of the target bar was vertically centered along the right edge of the box. Respectively, the fixation spot and the target bar translated at oblique angles of 45° and 22.5° down and to the right over distances of 3.1° and 5.7°, corresponding to speeds of 7.6°/s and 14°/s.

All participants completed 150 trials for each condition for a total of 450 trials in a single session (3 conditions × 6 interleaved staircases/condition × 25 trials/staircase).

Experiment 3

In Experiment 3 we sought to verify that the dynamic nature of the stimulus is a key factor driving the DISC effect. Specifically, we compared the size-contrast effect for the dynamic version of the stimulus with that found under comparable, but static conditions.

Experiment 3 contained two conditions (Table 1). For comparison, we replicated the Full Oblique condition (Figure 3 and Movie 1) and, in addition, included a nondynamic Static Frames condition. The initial and final configurations of the Static Frames condition (Movie 9) were identical to the Full Oblique condition, but during the 400-ms animation period the box and the bar were not shown. In other words, the dynamic phase consisted only of a moving fixation point. At the end of the animation period the full stimulus reappeared with the size and position of the box and bar matched to the final position of the Full Oblique condition. Participants viewed this still frame for 200 ms before the box and bar were extinguished. Participants then indicated whether the bar appeared to have grown or shrunk in the final configuration compared to the initial configuration.

Participants completed 150 trials for each condition for a total of 300 trials in a single session (2 conditions × 6 interleaved staircases/condition × 25 trials/staircase).

Analyses

Data from all trials of a given condition, independent of the staircase procedure, were combined to calculate psychometric curves (Leek, 2001; Leek, Hanna, & Marshall, 1992) describing the relationship between the growth rate of the bar and the participant's perception of bar size. We plotted the proportion of trials in which the participant reported that the bar was growing as a function of the actual growth of the bar in units of percentage of the initial bar size (see Figure 4 for an example). Given our two-alternative forced choice paradigm, we used the following sigmoidal shaped binomial-logit function to model the data (Wichmann & Hill, 2001) for each condition and participant independently using the MATLAB *glmfit* command:

$$f(x) = e^{b1+xb2}/(1 + e^{b1+xb2})$$

The point of subjective equality (PSE) was determined by interpolating the chance level response

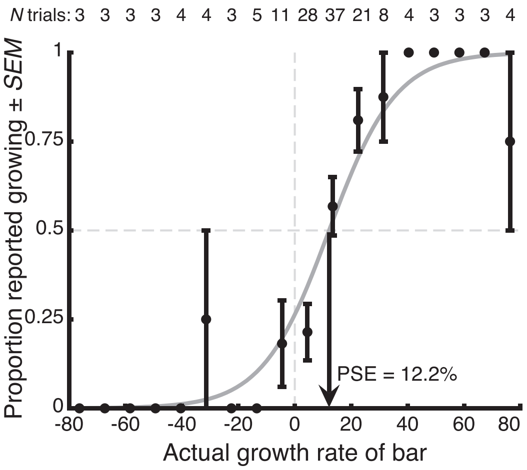


Figure 4. Example of a psychometric curve for the Full Oblique condition from one representative subject. The proportion of trials in which the participant reported that the target bar was growing is plotted against the actual growth rate of the bar. Positive growth rates indicate that the bar was physically growing, and negative growth rates indicate that the bar was physically shrinking. The total number of trials performed at each growth rate across six adaptive staircases is shown across the top. The raw data (circles) were modeled with a sigmoidal shaped binomial-logit function (solid gray line). The black arrow indicates the PSE, defined as the growth rate at which the fitted curve crossed 0.5 (horizontal dashed gray line). The PSE (12.2%) represents the growth rate at which the participant had an equal probability of perceiving the bar as shrinking or growing for a given condition. If no illusory percept was observed, we would expect a PSE of zero (vertical dashed gray line). Error bars represent *SEM*.

probability (0.5) from the function fit to the data (PSE $= -b_1 / b_2$). The PSE represents the growth rate at which the participant had an equal probability of perceiving the bar as shrinking or growing for a given condition. If there were no illusory DISC effect (i.e., veridical perception), we would anticipate a PSE of zero. Alternatively, if the DISC effect was perceived, we would anticipate a PSE greater than zero as physical growth of the target bar would be necessary to cancel or null the illusory reduction in perceived size. We note that we obtained similar results when we defined PSEs based on the average of the last five reversals of each independent staircase.

To avoid the assumptions of parametric statistical tests, we analyzed the data using a series of standard nonparametric tests and randomization procedures. However, we note that when the data were analyzed using parametric alternatives, the significance and the interpretation of the results were not qualitatively different. To determine whether the DISC effect was observed for each condition, PSEs were compared against zero using a nonparametric Wilcoxon signed-rank test. To determine whether experimental manipulations in the stimulus influenced the magnitude of the DISC effect, pair-wise comparisons across conditions within an experiment were performed using a two-tailed nonparametric permutation test for paired data. The mean difference in PSEs across two conditions was compared to a distribution of differences obtained for every possible permutation of each participant's values (number of permutations $= 2^N$, where N is the number of participants for that experiment; $n_{perm} = 32{,}768$ for Experiment 1; $n_{perm} = 2{,}048$ for Experiments 2 and 3). This is equivalent to randomly flipping the sign of the PSE difference across the two conditions for each participant. For this test, the p-value was defined as the proportion of random permutations of the data that yielded a difference in the PSEs for two conditions that was equal to or greater than the actual observed difference. The paired comparisons followed an initial nonparametric Friedman's test for repeated-measures data to verify a main effect of condition. As we only made a small number of a priori comparisons in each experiment informed by our experimental design and hypotheses, we report uncorrected p-values and assess statistical significance using an α of 0.05.

Results

PSE

For one representative participant from Experiment 1, Figure 4 shows the proportion of trials in which the participant reported that the target bar was growing as a function of the actual growth of the bar for the Full Oblique condition and the corresponding psychometric function that was fit to the data from which the PSE was interpolated. For the example shown in Figure 4, the PSE was 12.2%.

Experiment 1: An interaction between size contrast and other dynamic factors underlies the DISC effect

In Experiment 1 we sought to reproduce our original observation with a controlled stimulus and to explore the contribution of dynamic changes in size contrast, eye movements, and stimulus motion in modulating the magnitude of the DISC effect. This experiment included six conditions (Table 1): Full Oblique, Full Horizontal, Stationary Bar, Full Opposing Horizontal, Fixed Eyes, and Pure Size-Contrast. We first consider the five conditions completed by all subjects and then consider the Pure Size-Contrast condition at the end of this section. Overall, the results show that the DISC effect cannot be completely explained by changes in

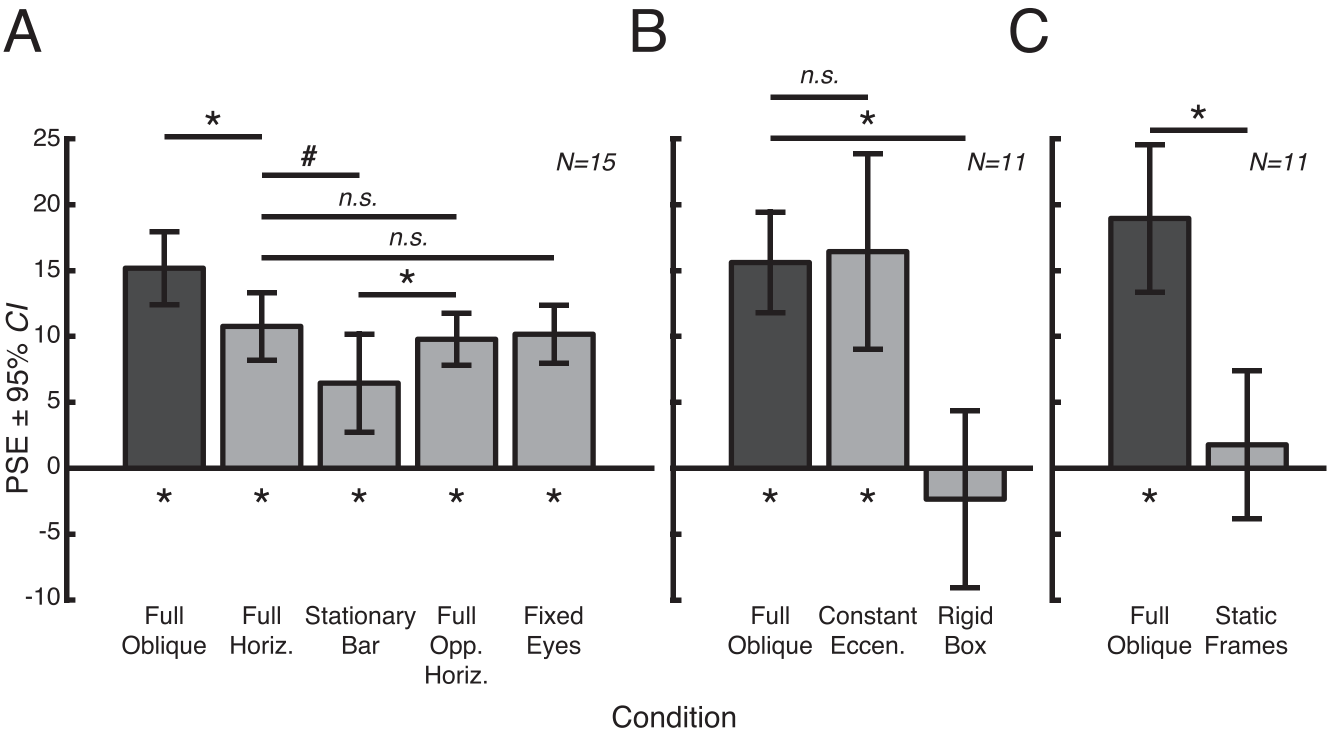


Figure 5. Mean PSEs for Experiments 1 (A), 2 (B), and 3 (C). The darker bars represent the Full Oblique condition, which was the identical in all three experiments. Symbols below the bars indicate the significance of one-sample comparisons against zero (Wilcoxon signed rank test) to test for significant illusory percepts. Symbols above the solid lines indicate the significance of pairwise comparisons (permutation test), the subset of which was selected based on a priori hypotheses and experimental design. *$p < 0.05$, #$p = 0.055$, and *n.s.* = nonsignificant difference. Error bars represent 95% confidence intervals.

relative size between the box and the bar. Rather, size contrast interacts with other dynamic components, such as eye movements and changes in the spatial position of the bar, to drive the DISC effect.

Figure 5A shows the mean PSE across participants for the first five conditions of Experiment 1. PSEs were significantly greater than zero for all of these conditions ($p < 0.013$, one-sample Wilcoxon signed rank test) indicating that the bar had to be physically growing for participants to perceive it as not changing in length over the course of the animation. Friedman's test revealed a significant difference among the distributions of PSEs across the five conditions ($\chi^2_{(4)} = 17.5$, $p = 0.0015$). We explored this main effect of condition more closely using a set of a priori comparisons based on the experimental design and hypotheses for Experiment 1.

The Full Oblique (Movie 1) and Full Horizontal (Movie 2) versions of the stimulus contained all four dynamic factors: a relative size change, a change in the spatial position of the bar, a change in retinal eccentricity, and eye movements. These conditions were matched for retinal stimulation, but contained different motion vectors of the stimulus elements. The magnitude of the illusory percept, as quantified by the PSE, was significantly greater for the oblique motion vector of the Full Oblique condition ($M = 15.2\%$) than the horizontal motion vector of the Full Horizontal condition ($M = 10.8\%$; $p = 0.002$, permutation test), and was in fact the most effective stimulus configuration that we tested. However, given that the remaining conditions of Experiment 1 all contained horizontal translations of the stimulus elements, we used the Full Horizontal condition for comparison.

In the Stationary Bar condition (Movie 3), the spatial position of the target bar remained fixed throughout the trial. The PSEs for this condition ($M = 6.5\%$) were lower than those for the Full Horizontal condition ($M = 10.8\%$), although this difference was only marginally significant ($p = 0.055$, permutation test). Thus, when the bar was not translating in space, the magnitude of the illusion was diminished. This was not a result of the fact that the eye movement was directed away from the target bar in the Stationary Bar condition and towards the target bar in the Full Horizontal condition. The Full Opposing Horizontal condition (Movie 4), which also contained an eye movement directed away from the bar, yielded a PSE ($M = 9.8\%$) that was significantly larger than for the Stationary Bar condition ($M = 6.5\%$; $p = 0.043$, permutation test), but not significantly different than those for the Full Horizontal condition ($M = 10.8\%$; $p = 0.53$, permutation test). Overall, these results suggest that a stationary bar diminished the influence of the expanding box on the perception of the size of the bar.

One possibility is that retinal image size of a stationary object can be more easily tracked across other dynamic changes, such as pursuit eye movements. With less uncertainty in the size information provided by the retinal image, less weight is given to the relative size information provided by the expanding box. However, as noted above, perception was not veridical in this case and there was still a significant illusion.

In the Fixed Eyes condition (Movie 5), participants fixated a stationary spot throughout the duration of the animation. PSEs for this condition ($M = 10.2\%$) did not differ significantly from the Full Horizontal condition ($M = 10.8\%$; $p = 0.64$, permutation test). This suggests that eye movements are not a necessary component for the DISC effect. However, as can be experienced in Movie 6, we noted that there was little-to-no illusory effect when the expanding box was the only dynamic component in the stimulus. In other words, the DISC effect is more than a straightforward illusion of size contrast.

To confirm this observation, we ran six of the participants from Experiment 1 in this Pure Size-Contrast condition (Movie 6) in a separate session. PSEs for the Pure Size-Contrast condition did not differ significantly from zero ($M = 4.5\%$, $p = 0.\ 25$, one-sample Wilcoxon signed rank test; note also that one participant had a very large PSE of 21.6%, which skewed the overall mean), indicating that perception was generally veridical in this condition. Moreover, PSEs for this condition were significantly lower than PSEs derived from the same six subjects in the Stationary Bar condition (Movie 3; $M = 11.1\%$; $p = 0.031$). Thus, the relative size change between the box and the bar was not sufficient to drive the DISC effect and, importantly, cannot account for illusory percept in the Stationary Bar condition. Rather, it is the interaction between the relative size change and other dynamic factors such as eye movements and motion of the target bar that underlies the DISC effect.

Experiment 2: Changes in surround size are necessary for the DISC effect

Experiment 1 showed that size contrast is not sufficient to explain the DISC effect. However, the results do not address whether size contrast is a necessary component. In Experiment 2 we investigate this question, as well as the potential role of dynamic changes in target eccentricity in the DISC effect. This experiment included three conditions (Table 1): Full Oblique, Constant Eccentricity, and Rigid Box. Overall, the results show that changes in relative size, but not eccentricity, are necessary for the DISC effect.

Figure 5B shows the mean PSE across participants for all conditions of Experiment 2. First, it is worth noting that the effect for the Full Oblique condition of Experiments 1 and 2 are of similar magnitudes demonstrating the robust and replicable nature of the DISC effect. In Experiment 2, PSEs were significantly greater than zero for the Full Oblique condition (Movie 1, $p = 0.003$, one-sample Wilcoxon signed rank test) and the Constant Eccentricity (Movie 7, $p = 0.01$, one-sample Wilcoxon signed rank test) indicating that in both cases the bar had to be physically growing for participants to perceive it as not changing in length over the course of the animation. In contrast, PSEs for the Rigid Box condition (Movie 8) did not differ significantly from zero ($p = 0.83$, one-sample Wilcoxon signed rank test), indicating that perception was generally veridical in this condition. Friedman's test revealed a significant difference among the distributions of PSEs across the three conditions ($\chi^2_{(2)} = 16.9$, $p = 0.0002$). We explored this main effect of condition more closely using a set of a priori comparisons based on the experimental design and hypotheses for Experiment 2.

PSEs for the Constant Eccentricity condition ($M = 16.4\%$) did not differ significantly from the Full Oblique condition ($M = 15.6\%$; $p = 0.91$, permutation test). Thus, keeping the target bar at a fixed eccentricity relative to fixation spot did not have a significant effect on the magnitude of the illusion. Although this suggests that eccentricity is not a necessary component, changes in target eccentricity may be one dynamic factor that interacts with the expanding surround to drive the DISC effect (see Pure Size Contrast above).

PSEs for the Rigid Box condition ($M = -2.4\%$) were significantly lower than those for the Full Oblique condition ($M = 15.6\%$; $p = 0.03$, permutation test). When the size of the box is held constant, observers do not experience illusory percepts of size at all, even in the presence of other stimulus motion and eye movements. Thus, the dynamic change in the size of the surrounding box is indeed a primary and necessary component to produce the DISC effect. In conjunction with the observations from the Pure Size-Contrast condition above, these data demonstrate that size contrast is a necessary factor, but by itself cannot sufficiently explain the magnitude of the illusory percept.

Experiment 3: The DISC effect depends on the dynamic nature of the stimulus

In Experiment 3, we sought to verify that the dynamic nature of the stimulus is a key factor driving the DISC effect. This experiment included two conditions (Table 1): Full Oblique and Static Frames. The results show that the DISC effect is only observed under dynamic stimulus conditions.

Figure 5C shows the mean PSE across participants for both conditions of Experiment 3. PSEs were significantly greater than zero for Full Oblique condition

(Movie 1, $p = 0.001$, one-sample Wilcoxon signed rank test), replicating the results from Experiments 1 and 2. In contrast, PSEs for the Static Frames condition (Movie 9) did not differ significantly from zero ($p = 0.90$, one-sample Wilcoxon signed rank test), indicating that perception was generally veridical in this condition. A paired comparison between these two conditions revealed that PSEs for the Full Oblique condition ($M = 19.0\%$) were significantly higher than for the Static Frames condition ($M = 1.8\%$; $p = 0.001$, permutation test). This demonstrates that the dynamic nature of the DISC stimulus is a principal factor contributing to the illusory percept, distinguishing it from static size-contrast illusions (see also Movie 1 and Figure 2).

Discussion

Here we introduce a novel size-contrast illusion termed the DISC effect, which reveals that under certain circumstances a dynamic and continuous change in the size of a surrounding object dramatically influences the perceived size of an inner target object (Movie 1). Our results show that this illusion is robust and reproducible, occurring across a variety of dynamic manipulations of the stimulus.

We identified four dynamic changes that may contribute to the magnitude of the DISC effect: (a) the relative size change between surrounding box and inner bar; (b) the change in the real-world position of the bar; (c) the change in retinal eccentricity of the bar; and (d) the execution of a smooth pursuit/saccadic eye movements. By systematically removing each of these factors from the full version of the stimulus, we show that the DISC effect is primarily driven by the change in relative size between the surrounding box and the inner bar, but that the illusion requires the presence of additional dynamic factors.

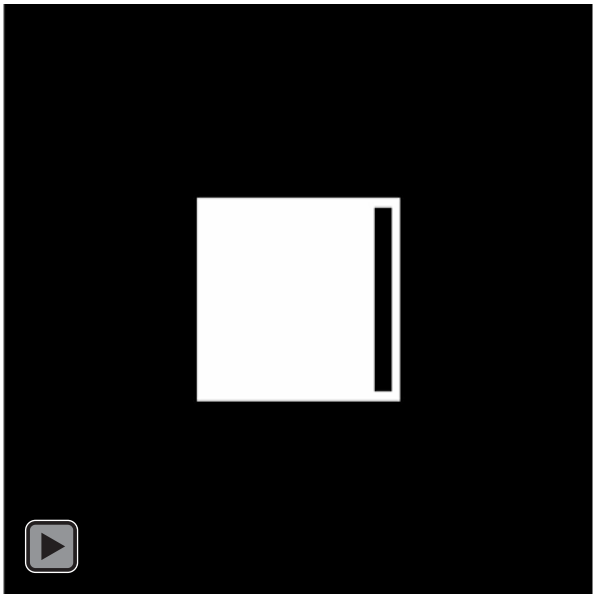
The relative size change between the surrounding box and the inner bar appears to be a necessary factor for the DISC effect, as indicated by the fact that there was no illusory percept of bar size when the surrounding box was static and unchanging (Experiment 2, Rigid Box condition, Movie 8). However, although the relative size change was necessary for the DISC effect, it was not sufficient; in isolation, an expanding box did not alter the perception of the bar's length (Experiment 1, Pure Size-Contrast condition, Movie 6). Thus, the DISC effect is a size-contrast illusion that is driven by the interaction between a relative size change and other dynamic factors, such as eye movements and stimulus motion.

The magnitude of the illusion was not diminished in the Fixed Eyes condition, which did not include eye movements (Movie 5). This is perhaps surprising, given the spatial distortions that can occur during smooth pursuit and saccadic eye movements (Hamker, Zirnsak, Ziesche, & Lappe, 2011; Schutz, Braun, & Gegenfurtner, 2011). However, it is not clear that the types of spatial distortions previously reported during eye movements would affect the perceived vertical extent of a moving bar. It remains an open question as to whether the vertical component of the eye movement is a contributing factor to our observation of the largest magnitude illusion in the Full Oblique stimulus.

As with eye movements, the magnitude of the illusion was not diminished when changes in target eccentricity were removed in the Constant Eccentricity condition (Movie 7). Although there is some evidence that the size of an object is perceived to be smaller for peripheral stimuli (Bedell & Johnson, 1984; James, 1890; Helmholtz, 1867), this effect is modest and our data indicate that it is not a principal factor for the DISC effect.

Interestingly, when the target bar was not translating in real-world coordinates (Stationary Bar condition, Movie 3), and the other three dynamic features were present, the magnitude of the illusion was diminished. Thus, whereas some form of additional stimulus motion in conjunction with the relative size change is necessary for the illusion, a change in the real-world position of the bar seems to be particularly effective.

In the case of size perception, environmental cues (e.g., changes in retinal image size, relative size, and perceived depth) may drive the internal representation of an object's size to be updated, if such cues are strong enough. Our data show that certain cues, such as relative size, may be weak and ineffective under some conditions, but robustly effective under others. What aspect of the DISC stimulus is triggering the illusion and leading to the pattern of results that we observed? We propose that the visual system is weighting the different sources of information that contribute to size perception based on the level of uncertainty in the retinal image size of the object. Whereas the growing box normally has a weak influence on the perceived size of the target bar, this influence is enhanced when other dynamic changes in the environment lead to uncertainty in the retinal size of the bar. Smooth pursuit and saccades lead to retinal jitter and the need to cancel out motion induced by eye movements. Changes in target eccentricity require the integration of the retinal image across different portions of the retina to track the same object. Both of these contribute to noise in the retinal image size of an object, and therefore, the need to inform size judgments based on other available information. Interestingly, the retinal image of a stationary bar in real-world coordinates, even in the presence of eye movements and increasing target eccentricity, appears to be tracked more easily, leading to less uncertainty and a weaker illusory effect.



Movie 10: Apparent transformational motion stimulus. The DISC illusion can be observed when two static frames are presented sequentially and without a delay between frames. Click on the image to view the movie. Movies are best viewed in looped mode.

An alternative explanation for the observed pattern of results may be that in conditions in which we observed an illusory effect the target bar was perceptually grouped with the contextual surround. However, an objective rule that governs this grouping is not obvious. First, the conditions of Experiment 1 (excluding the Pure Size-Contrast condition) were matched for retinal stimulation. Thus, the configural relationship between the target bar and the surrounding box was consistent across conditions; in each case the target bar was encapsulated by the expanding box and always at the same relative distance from its edge. Second, as can be experienced by viewing the movie demos (e.g., Full Horizontal condition, Movie 2), the magnitude of the illusion is greatly diminished by fixating the target bar rather than the red fixation point. It is unclear why this would lead to the target bar being "ungrouped" from the expanding box. In contrast, this observation is nicely explained by the retinal uncertainty hypothesis outlined above because visual acuity is greatly enhanced near the fovea. Thus, we conclude that the DISC effect represents a novel illusion that is driven by the interaction between size contrast and other dynamic factors that increase retinal uncertainty.

Throughout this manuscript, we have considered the DISC effect to be fundamentally a size-contrast illusion. However, an alternative explanation may be one of dynamic size constancy. One might argue that the expanding box in the DISC stimulus is consistent with the stimulus getting closer, and since the retinal image of the bar is not growing as expected, the bar is perceived to be shrinking. This is the explanation put forth for two perceptually related illusions, the shrinking building illusion (Fukuda & Seno, 2011), in which a distant building viewed through a window appears to shrink as you move closer to the window, and the StarTrek Illusion (Qian & Petrov, 2012), in which dots in an expanding optic flow field appear to shrink (as well as increase in brightness). Both illusions are driven primarily by changes in perceived depth due to self-motion (shrinking building illusion, Fukuda & Seno, 2011) or optic flow cues (StarTrek illusion, Qian & Petrov, 2012). Schrater, Knill, and Simoncelli (2001) showed that changes in stimulus size (i.e., "scale-change" information) could substitute for optic flow information and influence perceived depth. In addition, in the Constant Eccentricity condition (Movie 7), there is an illusory reduction in the distance between the fixation spot and the bar as the box expands, which is consistent with a size constancy effect. However, we feel that size constancy does not offer a compelling explanation of the DISC effect. First, it is the authors' impression, and the reader may concur by viewing the movie demos (see Movie 1, best viewed in "looped" mode), that the DISC stimulus does not induce a strong perceived change in depth, unless the observer exerts great top-down influence. The observer may also notice that if they are able to self-induce modulations in perceived depth the magnitude of the size illusion is not greatly affected. We note, however, that the size contrast and size constancy hypotheses make similar predictions in many cases. Given that we did not explicitly control or quantify perceived distance in our experiment, fully dissociating these competing hypotheses is left to future studies.

Although the dynamic nature of the illusion is dependent on the presence of motion in the stimulus (see Experiment 3), we noticed that a smooth change in the stimulus is not critical, as long as there was a perception of motion of the stimulus components. As seen in Movie 10, the illusion is subjectively strong when the two frames depicting the endpoints of the Full Oblique condition (Figure 2) are presented sequentially and without a delay between frames. Under these conditions, there is an induction of apparent transformational motion (Hikosaka, Miyauchi, & Shimojo, 1991; Tse, Cavanagh, & Nakayama, 1998). In apparent transformational motion, although there is no actual motion between the two frames, the perception is of a continuously, though quickly, changing form from one frame to the next. In our case, the size of the box is perceived to rapidly expand and contract. Thus, we would expect that any stimulus that activates the neural circuits for motion perception (Tse, 2006) would be sufficient for the DISC effect.

Finally, it is worth noting the DISC effect may asymptote over the course of the dynamic animation period that we selected. In the case where the target bar was actually growing, some of our participants reported that there was initially a strong percept of a shrinking bar followed by a percept of a growing bar. If subjects based their responses on the perceived physical change in the size of the target observed at the very end of these trials, despite having observed an illusory shrinkage of the target at the beginning of the trial, this would lead to an underestimation of the magnitude of the DISC effect. This may explain why the DISC effect is subjectively more compelling than static size-contrast illusions, yet the empirically derived magnitude of the DISC effect in our strongest (Full Oblique) configuration ($M = 16.4\%$ across Experiments 1, 2, and 3) is comparable to reported magnitudes for classic size-contrast illusions, such as the Ebbinghaus illusion (up to ~18%, Roberts et al., 2005). The reader may experience the qualitative difference between these illusions for himself or herself by comparing the percept produced by the classic size-contrast illusions presented in Figure 1 and that of the DISC stimulus in Movie 1. Consistent with this subjective sensation, the non-dynamic Static Frames version of our stimulus (Experiment 3, Movie 9) led to no illusory percept (see also Figure 2).

Conclusion

In conclusion, the DISC effect demonstrates that the contribution of relative size to judgments of stimulus size is modulated by other dynamic factors, including changes in the spatial position and retinal eccentricity of a target object and the execution of eye movements. Given the compelling nature of this effect and the inherently dynamic nature of our visual environment, these factors are likely to play an important role in everyday size judgments.

Keywords: size perception, form-motion interaction, size illusion, motion illusion

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