Introducing the scintillating starburst: Illusory ray patterns from spatial coincidence detection

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Abstract

Here, we introduce a novel class of visual illusion, the “Scintillating Starburst”, which features illusory scintillating rays or beams. We show empirically what combination of factors modulate how an observer experiences this kind of stimulus. We explain how the illusion arises from the interplay of known visual processes, specifically magnocellular and parvocellular dynamics and relate the effects of these ray patterns to other known visual illusions such as illusory contours.

Introduction

Illusions have played a key role in understanding the principles of perceptual processing (Purkinje, 1825; van Buren & Scholl, 2018), although this notion is not entirely without detractors (Braddick, 2018; Rogers, 2019). One important reason why illusions can be helpful is that they allow us to distinguish the mere sensation of physical object properties from the perceptual experience. This is perhaps clearest in the case of illusory contours. If contours are defined by a sharp change in luminance, it is hard to tell whether the observer “directly” perceives objects in the environment “as they are” or if the percept is constructed in the mind of the observer, because the output of a photometer and perceptual judgments agree (Gibson, 1978; Fodor & Pylyshyn, 1981). Conversely, illusory contours are not defined by changes in luminance, and would be invisible to a photometer, whereas human observers readily perceive them. One example of this is Kanisza’s triangle, which most observers perceive as a bright triangle occluding three black circles - as opposed to the three black pac-man-like shapes are actually defined by luminance (Kanisza, 1955). This phenomenon is an instantiation of a broader principle, by which organisms interpret scenes in ways that require the fewest assumptions, or are probabilistically most plausible (Koffka, 1935; Maniatis, 2008). In this case, it is more likely that 4 common shapes (circles and triangles) are in this scene than 3 uncommon shapes (pac men) that are arranged in this fashion by sheer coincidence. There are even neurons in prestriate cortex that seem to take such contextual considerations into account and respond to illusory contours as if they were luminance defined contours (von der Heydt et al, 1984).

Here, we introduce a related, but novel type of stimulus that evokes illusory rays that seem to shimmer or scintillate, see figure 1.

Figure 1. The “scintillating starburst” stimulus. This stimulus is made up of several interlocking polygons with faces that bisect each other (see Method section for details). Most observers perceive fleeting rays, beams or lines emanating from the center that appear to be brighter than the background.

To our knowledge, this class of ray patterns has not been previously described (Bach, 2005; Shapiro & Todorov, 2017). The purpose of this manuscript is to introduce a novel type of ray pattern and to explore the space of stimulus parameters that modulate subjective experiences of ray strength in one instantiation of this class - the “scintillating starburst” in the hopes of understanding what neural and cognitive processes might underlie this phenomenon.

Method

We were interested in investigating what modulates the visual experience of the scintillating starburst stimulus. To do so, we employed the empirical paradigm outlined below.

Stimuli

The “scintillating starburst” stimulus seen in figure 1 elicits transient shimmering rays that seem to be emanating from the center for most observers. This stimulus was designed in the following way. We used MATLAB (Mathworks, Inc., Sherborn, MA) to construct a regular heptagon (central angle = 51.143 degrees, rounded to 3 decimals), assuming a line width of 2 points, see figure 2A. Figure 2B was created by adding a 2nd, identical heptagon rotated by 25.71 degrees ($\pi/7$ radians) so that the faces of the two heptagons bisect each other. We call the image element depicted in Figure 2B a “strand”. Figure 2C was created by adding a scaled version (89.95%) of the heptagon in Figure 2A to itself. Figure 2D was created by the same principle, but now, the 2nd strand is again rotated such that the vertices of the heptagon faces that make up this strand also bisect each other. The scale factor was chosen so that the two strands just touch each other, in other words the vertices of the smaller heptagon bisect the midpoints of the larger heptagon. We call the image element depicted in figure 2C and D an “inducer ring” (not-bisecting and bisecting versions, respectively). The image in figure 2E was created by adding another not-bisecting inducer ring to 2C such that the 2nd ring is a scaled down version (66%). The image in 2F was similarly created by adding another bisecting inducer ring to 2D, using the same scale factor. Thus, 2E and 2F feature two not-bisecting and bisecting inducer rings each, respectively. Finally, figures 2G and 2H were created by adding an additional inducer ring using the same scale factor, so that these images are featuring 3 inducer rings. One could repeat this principle to create stimuli with even more inducer rings. One could also vary the number of vertices in the polygon.

Figure 2. An illustration of how the scintillating starburst stimulus was constructed. Top row: Non-bisecting stimuli, Bottom row: Bisecting stimuli. A: A single heptagon. B: Two heptagons with faces that bisect each other, which we call a “strand”. C: Two scaled heptagons - a “non-bisecting” strand. D: Two scaled strands of bisecting heptagons, making up one “inducer ring”. E: Two scaled non-bisecting rings. F: Two scaled bisecting rings. G: Three scaled non-bisecting rings. H: Three scaled bisecting rings. This stimulus corresponds to the “scintillating starburst stimulus” shown in figure 1, but on a white background and smaller.

In fact, we did just that to parametrically create visual stimuli varying in 5 stimulus dimensions: 1) Number of vertices of the polygon [3 levels: 3 5 7], 2) Contrast [3 levels: 0.1 0.55 1], 3) Line width of the innermost ring [3 levels: 0.5 1 1.5 points], 4) Number of inducer rings [3 levels: 2 4 6], 5) Whether the strands of the inducer rings bisect each other [2 levels: Yes and no].

Fully crossing these stimulus dimensions yields the set of 162 unique stimuli we used in this study. All other stimulus dimensions were kept the same across all stimuli so as to not further increase the number of stimuli in the set. All stimuli were presented on a white background at a size of 600x600 pixels, delivered remotely.

See figure 3 for an illustration of a representative sampling of this space as well as the average experienced ray strength (RS) evoked by these stimuli in our sample of observers. As you can see, our set of stimuli evoked a wide range of responses and

were effective in modulating the experience of the observers. The reason we picked these stimulus dimensions and not others is to avoid the curse of dimensionality - there is a vast space of visual parameters to vary, many of which have no impact on the effect. For instance, extensive piloting suggested that color, size or uncoiling the rings to yield non-radial ray patterns did not seem to affect experienced ray strength much.

Figure 3. A representative sample of 20 out of the 162 stimuli used in this study. Pictograms of the stimuli are arranged in increasing order of average ray strength reported by our sample of observers. Top rows: Weak ray strengths. These rows are predominantly made up of triangular polygons, low contrast stimuli and non-bisecting stimuli. 2nd to last row: Stimuli with moderate experienced ray strength - predominantly bisecting pentagons. Bottom row: These 5 stimuli evoked the strongest ray experiences. These stimuli consist of high contrast bisecting heptagons with several rings. This stimulus is made up of several interlocking polygons that bisect each others faces (see Method section for details). Most observers perceive fleeting rays, beams or lines emanating from the center that appear to be brighter than the background. The label above each icon indicates the level of the independent variable, in order (number of vertices per polygon, contrast, line width, number of rings and whether the polygon faces bisect each other). The RS value below each icon denotes the average experienced ray strength.

Participants

We recorded data from a total of 122 participants. We recruited naive observers from the NYU student community and the general public. We excluded data from 8 participants who completed the study implausibly fast (less than 2 seconds per

question, median response time per question = 6.08 seconds), 6 participants who reported that they did not respond seriously and from one participant with more than 3 missing responses. Importantly, we decided on these exclusion criteria before looking at any of the results. Thus, we retain data from $\frac{7}{8}$ of the initial sample for further analysis. In this sample, the median age was 19.5 years. 66 participants identified as female, 40 as male and 1 participant did not disclose a gender.

Task

All observers were asked to answer a number of questions about how strongly they experience the ray strength of these stimuli. Response options were ["I do not see any bright lines, rays or beams", "I maybe see bright lines, rays or beams but they are barely noticeable", "I see bright lines, rays or beams, but they are subtle and weak", "I clearly see bright lines, rays or beams", "I see strikingly bright lines, rays or beams"]. We took these response options to form an intuitive 5-point Likert scale and scored them as 0 to 4 in terms of ray strength (RS), respectively. All of these stimuli were presented in random order. In addition, we asked observers about the experienced ray strength of a conceptually similar stimulus - a chain pattern - immediately before and after the set of ray pattern stimuli. After that, we asked the observers questions about their subjective experience of other well known visual stimuli, see figure 4.

Figure 4. Other visual stimuli we used. A: Concentric “chains”, analogous to the scintillating starburst stimulus. B. Kanisza’s triangle. C. The scintillating grid. D. The “Dalmatian” (Gregory, 1970).

We subsequently asked questions about the vividness of their visual imagery using the first set of questions from the VVIQ (Marks, 1973) as well as questions about aspects of personality using the TIPI (Gosling et al., 2003) and the “dirty dozen” (Jonason & Webster, 2010). Finally, we asked demographic questions about age, socioeconomic status, race and gender for a total of 197 questions or trials.

This study was hosted online (SurveyMonkey.com) and all procedures were approved by the New York University Institutional Review Board (UCAIHS).

Data analysis

All data were analyzed with MATLAB (Mathworks, Inc., Sherborn, MA). Specifically, we used a 3x3x3x3x2 repeated measures ANOVA to analyze the data on the experienced ray strength of the 162 unique ring patterns. We used a pairwise t-test to analyze the experienced ray strength of the chain patterns presented before and after the ring patterns. The reason to use these tests is that within-subject tests have much higher power than between-subject tests (Wallisch, 2015), which is adequate given our relatively small sample size. We used correlation analyses - using Spearman correlations to account for the fact that our data was measured on an ordinal level - to analyze data from the other measures. This resulted in 14 additional tests, so we used a Bonferroni correction which lowered the significance level to 0.004 for these tests.

Results

Using the methods described above, we attempted to answer the following questions:

How do variations of stimulus parameters in different dimensions affect the perceived ray strength of observers when looking at scintillating starburst stimuli?

To answer this question, we performed a 5-way repeated measures ANOVA on the responses to the 162 ring stimuli. See table 1 for results.

Factor	df	F	p
Number of vertices	2	107.96	3.26e-31
Contrast	2	182.22	2.09e-43
Base linewidth	2	147.8	3.07e-38
Number of rings	2	413.42	7.87e-67
Bisecting faces	1	258.91	8.25e-28

Table 1: Repeated measures ANOVA table.

All five main effects were significant, with variable modulation range, see figure 5 for an illustration of the means plots of the main effects.

Figure 5. Means plot of main effects of the repeated measures ANOVA from table 1. Each panel corresponds to a different independent variable (levels are on the x-axis) whereas the y-axis represents the average experienced ray strength (RS) reported by our observers.

As you can see, the number of rings modulates the experienced ray strength most strongly, whereas the modulation from changing the base line width is only modest. However, note that - by themselves - none of these parameters elicit clear or strong ray experiences. This suggests that the “full” experience of these rays stems from a combination of factors. See figure 6 for an illustration of all 2-way interactions.

Figure 6. 2-way interaction plots between all independent variables used in the repeated measures ANOVA. X-and Y-axes denote levels of the independent variable in question. The color represents the average reported ray strength, see color bar on the right.

As you can see, even the strongest 2-way combinations, i.e. many bisecting rings or many vertices plus many rings by themselves only elicit weak responses, on average. This suggests both that the modulation range of perceptual experiences as a function of stimulus parameters is large and that a strong ray experience relies on the optimal combination of many stimulus dimensions at once.

In addition, we suspect that combining individual responses by taking the mean does not fully represent the fine structure of responses evoked by these stimuli. Thus, in figure 7, we present the stimulus space ordered by increasing mean response in terms of response histograms.

Figure 7. Ray strength responses evoked by all 162 stimuli in our set, arranged by increasing average ray strengths. The label above each histogram denotes the combination of independent variable levels that corresponds to the stimulus, as in figure 3. The bars represent the response histogram evoked by each stimulus. The modal response is colored in terms of the following color code: Blue: No rays. Green: Maybe rays. Yellow: Subtle rays. Orange: Clear rays. Red: Striking rays.

As expected on the basis of the ANOVA means plots, much of our stimulus space did not evoke strong responses in most of our observers. Only a few stimuli are

experienced by most observers as exhibiting strikingly bright rays, when all parameters combine optimally in all of the dimensions we varied.

Does looking at ray patterns evoke a perception of shimmering rays in other stimuli that did not previously evoke them?

When piloting the stimuli, we could not help but note that our perceived ray strength seemed to increase for stimuli that had not previously elicited ray experiences, particularly after looking at ray patterns for extended periods of time. To test for this possibility, we presented observers with a similar chain pattern (see figure 4A) immediately before and after judging the ring patterns. Performing a pairwise t-test on this data supports this hypothesis - observers do experience significantly stronger rays from chain patterns after being exposed to rays for a while ($t = 2.19$, $df = 104$, $p = 0.03$).

What factors account for the large individual differences in the experience of the rays?

As you can see in figure 8, there is a considerable variation of subjective ray strengths. Some observers almost never see rays whereas a few others see them everywhere with most observers somewhere in between these extremes.

Figure 8. Histogram of average ray strength evoked by all stimuli, across all observers. X-axis: Average ray strength reported. Y-axis: Number of observers reporting this average ray strength.

This does raise the question whether we can account for these differences with systematic factors that vary between observers. We tested the following factors: Vividness of visual imagery, perception of other visual stimuli (those in figure 4), neuroticism, extraversion, openness, agreeableness, conscientiousness, psychopathy, machiavellianism, narcissism, age, gender, race and socioeconomic status. Only narcissism was positively associated with experienced ray strength such that $p < 0.05$ ($r = 0.27$, $p = 0.0048$). However, this association is actually not statistically significant after doing the Bonferroni correction for performing 14 of these tests. Thus, we can not ascertain in this manuscript why individuals report to experience different average ray strengths when viewing scintillating starbursts.

Discussion

In this manuscript, we introduced a novel kind of stimulus that evokes ghostly or ephemeral illusory rays which appear to shimmer or scintillate. We ascertained that the ray strength experienced by observers when viewing this stimulus type is modulated by the number of vertices of the polygons, contrast, the line width of the rings, the number of rings and whether the strands are bisecting or not. Finally, we established that looking at this kind of stimulus for extended periods of time makes the reported ray strength stronger for chain-like stimuli.

We are aware of several limitations of this research. First, this stimulus class seems to be modulated by many parameters over a wide range of values, which creates a combinatorial explosion. For instance, if we even just added uncoiled versions of the strands to the fully crossed design, observers would have been presented with twice the number of stimuli - 324 trials. Moreover, using just 5 instead of 3 levels per parametric dimension would have yielded 1,250 distinct versions of these ray pattern stimuli, which is impractical to use in a single experiment. Thus, we are aware that we are undersampling the full stimulus space.

Second, the 0.1 contrast condition was probably too weak to be seen readily, regardless of the other stimulus dimensions, establishing a floor effect. In hindsight, we should have used logarithmic spacing of contrast levels - 0.25, 0.5 and 1. However, because observers are unlikely to be using calibrated monitors in an online study anyway, this probably does not matter much as the visual effects of the scintillating starburst stimulus are fairly stable over a large parameter range.

Third, we were unable to ascertain the reason behind the large inter-individual variations in ray strength. This might not be unrelated to the prior point - we had no control over the specific viewing conditions such as monitor type, screen settings (e.g. brightness and contrast) or even viewing distance. There are other reasons why the distribution of reported ray strengths might be so broad. For instance, it might have been tighter if we had given people examples - using luminance defined rays - as to what we mean by “clear” or “striking”, but we did not do so in order not to bias observers by seeding them with our ideas of what the percepts should look like. Moreover, giving examples would have interfered with establishing a baseline for the effects evoked by the chain-like stimuli. It is also possible that we simply did not have enough power to probe subtle inter-observer differences, even if they existed (Wallisch, 2015). For instance, only a few observers did not see the scintillating grid (Schrauf, 1997) in figure 4C or the Dalmatian in figure 4D. There are other potential reasons for our failure to detect systematic inter-observer effects, for instance there are test-theoretical concerns about the validity of personality self-report measures (Kajonius et al., 2016) as well as concerns about restricted range for factors such as age of the observers (most of our participants were between 18 and 21 years old).

Finally, whereas we observed an effect of perceptual learning when looking at these stimuli - both ourselves and in our observers - we are unable to ascertain the reason behind this tendency to see rays in stimuli that did not previously evoke rays. Plausible explanations are either the establishment of perceptual priors or criterion shifts in the judgment of the vividness of the rays, but we cannot distinguish between these possibilities, as our study was not designed to do so.

Nevertheless, we believe that we have sufficient empirical evidence to elicit the key mechanism that underlies and brings about this phenomenon.

We attribute this effect to the workings of several known visual processes that work in conjunction to bring about the illusory scintillating rays, much like in the case of the “lilac chaser”, which is a combination of Troxler fading, after-images and the phi effect (Bach, 2005).

To understand the nature of this effect, we first note that the primate visual system features distinct subsystems that scan the environment in parallel. Two major streams are seeded by parasol ganglion cells that predominate in the periphery and midget ganglion cells that predominate in the fovea (Rodieck & Rodieck, 1998; Masland, 2001). Parasol ganglion cells project to magnocellular and midget ganglion cells to parvocellular neurons in the thalamus, respectively (Callaway, 2005). Importantly, the magnocellular pathway is associated with lower

spatial frequency selectivity, whereas the parvocellular pathway is associated with higher spatial frequency (Derrington & Lennie, 1984). Thus, cortical visual areas that are fed by the magnocellular pathway essentially see a low-pass filtered or blurry version of the image, whereas cortical visual areas in the parvocellular pathway receive a sharp version of the visual information. This is important due to a feature of our stimulus, see figure 9. Due to how the stimulus was constructed, the relative luminance density should be equal in all directions from the center if the luminance was a linear addition of the luminance of the strands. However, the rings that make up the stimulus are of uniform luminance. In other words, there is a relative imbalance where the strands intersect. In our case, this means that the strand intersections appear brighter than the rest of the stimulus in a low-pass filtered version of the image, much like the magnocellular pathway would (Movshon et al., 2003).

It stands to reason that the most compelling interpretation of this unlikely spatial alignment of bright “beacons” (see figure 9C) is that there is an actual bright line that is occluding the black rings, just like in a classical illusory contour. Peripheral vision simply does not have the resolution to discern that the bisection points are not actually brighter (Otten et al., 2016) and notoriously conflates multiple objects that fall in the same large receptive field (Pelli & Tillman, 2008; Guernsey et al., 2011, Guernsey & Board, 2012). We think that the reason the rays seems to sparkle - unlike classical illusory contours

Figure 9. The visual mechanism underlying the scintillating starburst effect. A: A 4-ringed starburst at high contrast. B: A low-passed version of this stimulus. As you can see, there are islands of relative brightness where the faces bisect. C: A surface plot of the stimulus in B. Note that there are aligned “beacons” of brightness that observers could mentally connect across the divides of full brightness (in yellow) between the rings. D: A version of the stimulus in A where the rings are made up of half-contrast strands. Only the bisection spots are at full contrast. E: A low pass filtered version of the stimulus in D. Note that there are no net bright spots in this blurry version, as the full contrast bisections blend in with the rest of the stimulus. F: This is the stimulus in D subtracted from the stimulus in A, akin to Movshon (2003). As you can see, bright “features” emerge in this subtractive version. It is these features, which correspond to the “beacons” in C, that the magnocellular visual system is connecting mentally. This stimulus appears to have even stronger rays, likely because the aligned bisection points are luminance-defined brighter, much like in a moire pattern.

(Kanisza, 1976) is that central vision does have the resolution to tell that the luminance in the bisection centers is actually not brighter (Westheimer, 1982). This dynamic competition between foveal (“no bright line is occluding the rings”) and peripheral vision (“it is likely that there is a bright line occluding the rings”) renders them so fleeting, as a function of eye movements. The sparkle comes from the “brighter than bright” phenomenology of the rays relative to the background, much like in similar illusions that involve scintillating stimuli that are dependent on

where the observer looks at the time (Schrauf, 1997). Note that other scintillating stimuli are also fundamentally due to dynamic competitions of underlying neural circuits (Pinna et al., 2002), echoing other illusions that rest on the interplay between foveal and peripheral vision (Shapiro et al., 2010). Moreover, if the stimulus falls in the far periphery, the rays disappear altogether, presumably because there is not enough resolution to resolve the “beacons” in figure 9C. This also supports the idea that the effect fundamentally derives from a competition between the interpretations of the two parallel visual systems, another instance of a “crowd within” (Vul & Pashler, 2008).

Thus, this stimulus - and its underlying mechanism - is at once similar, yet different from classical illusory contours and other scintillating stimuli. We want to be clear that this effect is also similar, yet different to several other phenomena: First, the pincushion illusion pertains to the perception of faint illusory lines that seem to crisscross a regular square lattice diagonally, particularly at low contrasts (Schachar, 1976) and especially when the points where the horizontal and vertical lines of the checkerboard lattice cross are color-enhanced (Roncato et al., 2016). There are several notable similarities and differences between this illusion and the scintillating starburst. Unless color enhanced, the pincushion illusion is subtle and most evident at low contrast, which is not the case for the scintillating starburst, which can be quite striking. Moreover, a salient feature of our stimulus is that the bisecting polygons are concentric, i.e. scaled versions of each other. This is notable because the pincushion illusion pertains to simple lattices, where each picture element is the same as the others. Another importance difference consists in the fact there is no correspondence between percept and Fourier Transform (FT) in the pincushion illusion (Schachar, 1976). In the scintillating starburst, the match between perception and FT is perfect, if the stimulus is made up of concentric bisecting polygons, see figure 10.

Figure 10. Starbursts and their FT. Left column: Stimuli. Right column: Corresponding FT.
 Top row: The 14 perceptual spokes in A) match the 14 spokes in the FT in B).
 2nd row: The 10 perceptual spokes in C) match the 10 spokes in the FT in D).
 3rd row: There are no spokes in the percept in E) , but the FT exhibits 14 spokes in F) because of the hexagonal structure of the stimulus.
 4th row: Even a single hexagon in G) exhibits the same FT structure in H, albeit at lower power

Vision scientists were taken by the observation that neurons in early visual cortex are tuned for spatial frequency (Enroth Cugell & Robson, 1966), suggesting that the visual system might effectively perform a linear systems analysis on the visual image (Campbell & Robson, 1968), although this view has been somewhat tempered as of late (Carandini et al., 2005).

In the case of the scintillating starburst stimulus, we report an intriguing relationship between visual percept and corresponding FT. A single polygon will exhibit a spoke-like structure in the FT (figure 10 G and H), and the FT power of the spokes will be stronger if there are more polygons with the same number of vertices (figure 10 F and H). However, by itself, this is not sufficient to evoke the percept of spokes in the mind of the observer. For that to happen, it is also necessary for the stimulus to be spatially arranged as concentric bisecting polygons. In that case, the number of spokes in the FT does match that of observers perceptually, in the case of heptagons 14 (figure 10 A and B) and in the case of pentagons 10 spokes both perceptually and in the FT (figure 10 C and D). In other words, whereas the power in the Fourier domain seems to be insufficient to yield percepts of illusory rays, in cases where stimuli are spatially arranged as concentric bisecting polygons, the power distribution in the two spatial frequency domains accurately predicts the visual percept of observers.

In spite of the differential behavior with regard to linear systems analysis, the pincushion illusion and the scintillating starburst share several features, i.e. the intersections of the repetitive grid patterns are also of the same luminance, not linearly superimposed, so the fact that diagonal lines emerge - and moreover, if there are more intersection points that go away if looking at them (Morgan & Hotopf, 1989) supports the notion that the pincushion illusion might be a special case of our more general effect.

A similar effect on grid-like lattices has been described as “phantom bands” (Motokawa 1949). Briefly, a rhombic alignment of the lattice seems to abolish the dark spots at the intersection points of the Hermann grid, instead dark “phantom bands” seem to appear. However, it has been pointed out that these are two separate phenomena that are not competing directly but can coexist in the same stimulus (Hamburger et al., 2012). Be that as it may, there are several important differences between phantom bands and the illusory rays in the scintillating starburst. First - like in the pincushion illusion, there are no components in FT of the rhombic grid lattice that correspond to the phantom bands. Second, our spatial stimulus layout does not correspond to a lattice at all. Importantly, there is sufficient background between the inducer rings to necessitate an unconscious inference that they are connected. Conversely, in a rhombic lattice, the phantom bands are luminance defined at low pass.

Similarly and more generally, *Moiré patterns* are interference patterns that result from striped regular gratings being overlaid with similar patterns (Oster 1968). Whereas the phenomenological appearance of these patterns can be striking, the beat patterns are actually present physically, in other words they are luminance defined patterns, unlike our stimulus.

Finally, the rays or beams observed to connect opposing bisection points of the polygons are reminiscent of the “spokes” illusion (Holcombe et al., 1999). In this illusion, perceived “spokes” emerge when fixating in the middle of revolving high contrast objects. Whereas it is the case that the rays stabilize and strengthen when the polygons of the starburst stimulus are rotating, the spokes illusion is fundamentally a motion illusion, whereas motion is not necessary in the starburst. Moreover, the spokes don't seem to appear immediately, yet the rays in the scintillating starburst appear to emerge instantly, and without a need to fixate in the center.

Thus, we conclude that we are here introducing a novel compound illusion that combines several visual processes to bring about the effect, much like the Lilac chaser. Our theoretical interpretation integrates all of the empirical evidence presented in this manuscript. We observed that the effect gets stronger if there are more rings and more vertices per ring (although piloting suggests that if there are too many vertices in a polygon, the stimulus becomes too indistinguishable from a circle and the effect decreases again). This will increase the number of coincidental spatial alignments, thus provide stronger evidence for a more compelling interpretation - an occlusion by a bright streak that goes away when looking at it directly, because it is incompatible with the information provided by the fovea. We also observed that the effect gets stronger with increased line width and contrast, both of which would render the ghostly bright dot at the bisection points stronger. Finally, we observed that bisecting the strands increases the effect, which makes sense as there are no - relatively - bright intersections without such overlapping strands. The fact that this effect results from the confluence of many factors also likely explains why it has remained unnoticed or unreported for so long - the only way to get strong effects from ray patterns is for all of these factors to be optimal. In retrospect, our stimulus design shares features of a Baravelle spiral (Nicholson et al., 1998). In general, stimuli created by the “ad quadratum” method and others like rose or rhodonea curves (Hall, 1992) can be perceived as exhibiting such imaginary patterns, if one looks for them. However, investigators of these patterns seemed more interested in their mathematical properties in the case of the rose curves and the actual spiral in the case of the Baravelle spiral. Note that coloring in this spiral, as has been done historically, abolishes the perception of these rays.

On that note, one remaining question - that we did not explore systematically in this study due to the curse of dimensionality - is whether the radial arrangement of the strands is necessary to get scintillating ray effects. Instead, we will show here that a radial arrangement is indeed not necessary, but the other theoretical mechanisms outlined above seem to apply, see figure 11.

As you can see, more intersection points yield more fleeting rays particularly if there are more strands to connect, particularly if the lines are thicker, but they do not have to be arranged radially or concentrically.

Figure 11. Beyond starbursts. In this figure, we explore arrangements other than radially arranged polygons. A: Two strands of thin lines, arranged linearly. B: Two strands of thick lines, arranged linearly. C: Six strands of thin lines, arranged linearly. D: Six strands of thick lines, arranged linearly. A superposition of several effects (thick lines, multiple lines) makes vertical illusory rays appear at the intersection points, but not for the others (A-C).

This novel effect opens avenues for future research. One question could be at which level of the visual hierarchy this effect arises. If it is similar to classical illusory contours, we would expect physiological correlates as early as V2, but not V1 (von der Heydt & Baumgartner, 1984), but it could manifest later, due to the interplay between foveal and peripheral vision which might happen at a subsequent stage of visual processing and awareness. Second, piloting suggests that subjective states like sleep might modulate the strength of the effect substantially, but this needs to be systematically verified, and in a larger sample. Similarly, it would be good to determine what accounts for the large reported differences in experienced ray strength between

observers in general. Third, it would be useful to empirically study the larger parameter space that we did not explore. We fixed all parameters other than the 5 dimensions we mentioned in this manuscript at constant values, so as to not increase the number of stimuli beyond what is feasible to accomplish in one study. For instance, the strands that make up a ring are scaled versions of each other. Small changes in this scale factor dramatically change the phenomenological appearance of the stimulus, but we kept this scale factor constant across all stimuli. Moreover, it seems likely that one could find interesting effects studying other, non-radial patterns and configurations beyond what we did in figure 11. Fourth, if our explanation of this mechanism is correct, changing the luminance of the bisection - and more generally intersection - points to compensate for the relative contrast in the low pass filtered image due to non-superposition should abolish the rays. It would be interesting to know how much contrast one has to add in order to prevent scintillating rays, but this would require the use of calibrated monitors, so is beyond the scope of online studies.

Finally, we wonder whether there is an individual threshold of evidence (the number of aligned intersection or bisection points) that a given observer needs in order to reliably perceive scintillating rays and their propensity to “connect the dots” (where coincidence is no longer subjectively consistent with parsimony) in other domains, such as the perception of constellations or the belief in conspiracy theories.

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Author contributions

MWK designed the stimuli. PW and MWK designed the study. PW recorded and analyzed the data. PW and MWK wrote the manuscript.

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