The scintillating grid illusion is enhanced by binocular viewing

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Abstract. The scintillating grid illusion is an intriguing stimulus consisting of a grey grid on a black background, with white discs at the grid intersections. Most viewers perceive illusory "scintillating" black discs within the physical white discs, especially at non-fixated locations. Here, we report for the first time that this scintillation percept is stronger when the stimulus is viewed binocularly than when it is presented to only one eye. Further experiments indicate that this is not simply because two monocular percepts combine linearly, but involves a specifically cyclopean contribution (Schrauf & Spillmann, 2000). However, the scintillation percept does not depend on the absolute disparity of the stimulus relative to the screen. In an intriguing twist, although the basic illusion shows more scintillation when viewed binocularly, when the illusion is weakened by shifting the discs away from the grid intersections, scintillation becomes stronger with monocular viewing.

1 Introduction

The scintillating grid illusion (Schrauf, Lingelbach, & Wist, 1997) is a variant of the Hermann grid in which white discs are placed at the intersections (Figure 1). This creates a powerful illusion of black spots flashing inside the white discs, particularly in peripheral vision and during saccadic eye movements (Schrauf, Wist, & Ehrenstein, 2000).

The reason for this illusion remains a mystery (Qian, Yamada, Kawabe, & Miura, 2009; Yu & Choe, 2006). However, its dependence on various parameters has been well documented. The scintillating effect requires the white discs to have at least twice the luminance of the grey grid, and is best when the disc luminance is around 10 times that of the grid and 100 times that of the black background (Schrauf et al., 1997). It depends on orientation, being strongest when the gridlines are vertical/horizontal as in Figure 1, and weakest when the entire pattern is rotated through 45° (De Lafuente & Ruiz, 2004). It is also weakened when the discs and grid are presented in different depth planes, with the scintillation all but abolished once the relative disparity between grid and discs exceeds 15 arcmin (Schrauf & Spillmann, 2000). One study has reported that the illusion can be obtained when the discs are presented to one eye and the grid to the other, implying that the illusion arises centrally, after binocular combination in primary visual cortex (Lavin & Costall, 1978). However, this has not been replicated, with other workers reporting that this dichoptic version of the grid simply produces binocular rivalry (Troscianko, 1982).
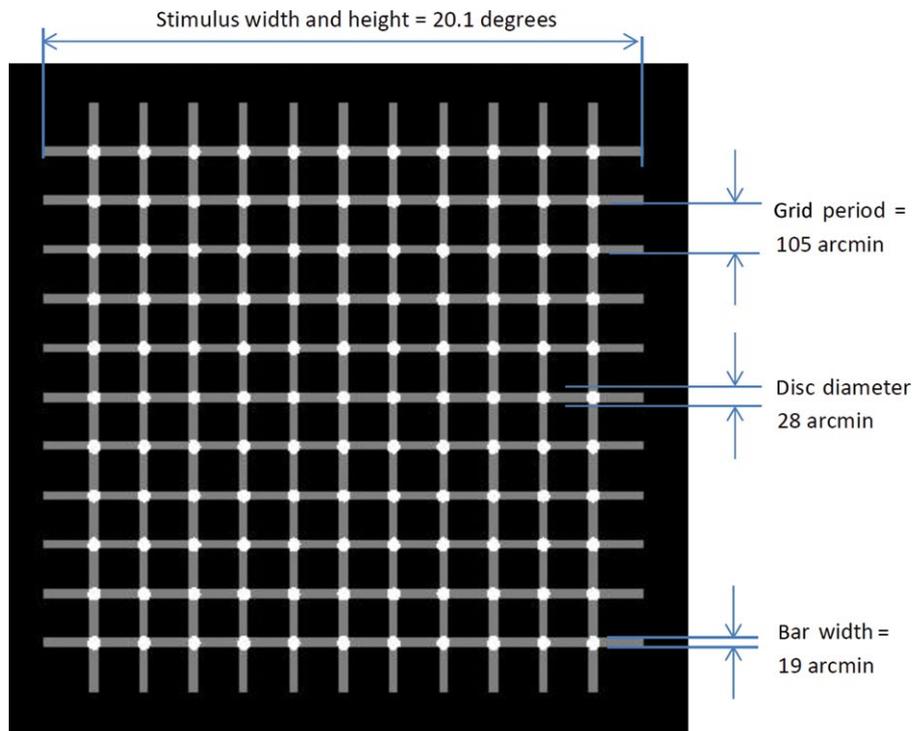
Figure 1. The scintillating grid illusion. This effect describes the black flashing within the white discs. This effect is stronger while scanning the grid and diminishes greatly at the point of steady fixation.

Here, we show that the illusion has a complex dependence on binocularity. It is weakened by monocular viewing when the discs are centred over the grid intersections, but strengthened when they are offset from the intersections. This has not previously been reported, and is at odds with one previous report.

2 Methods

2.1 Apparatus

Experiments were run on an ACPI PC under 64-bit Windows 7 with a NVIDIA Geforce9600GT graphics card. Stimulus code was written in Matlab (www.mathworks.com) using the Psychophysics Toolbox (www.psychtoolbox.org) (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). Stimuli were presented on a 23-inch LG 3D monitor (model number D2342PY) and viewed using 3D glasses. This monitor is a patterned-retarder passive 3D monitor that uses circular polarisation to separate the two eyes' images. The left and right images are presented on alternate pixel rows. It is easy to direct images to the appropriate eye using the Psychophysics Toolbox in "stereomode 100."

The interocular crosstalk is highly dependent on the viewing angle, since at oblique angles the line of sight to a pixel can pass through the other eye's retarder. For this reason, subjects viewed the screen with their head in a forehead-and-chin rest (UHCOTech HeadSpot), at a viewing distance of 70 cm. At the optimal angle, the interocular crosstalk measured with a Minolta LS-100 photometer was under 2%.

The resolution of the screen is 1920 × 1080 pixels, and its physical dimensions are 51 × 29 cm, both width × height. There are therefore 540 pixel rows in each eye. For calculating image dimensions, therefore, each pixel effectively subtended 1.3 arcmin horizontally and 2.6 arcmin vertically.

2.2 Stimuli

The basic stimulus is shown in Figure 1. We aimed to set stimulus parameters close to those in Schrauf and Spillmann (2000). The grid contained 11 horizontal and 11 vertical grey bars, each 19 arcmin in width, with a white disc of diameter 28 arcmin at each intersection. The period of the grid lines was 105 arcmin.

The luminance of the discs, grid, and background were respectively 50, 15, and 0.5 cd/m^2 in each eye, measured with the photometer through the corresponding lens of the 3D glasses. The Michelson contrast between the white discs and the grey grid was therefore about $C = 0.5$. In the monocular condition, the scintillating grid was presented in only one eye (i.e. on half the pixel rows); the other eye's image was black. This halved the total luminance. To distinguish between the effects of monocular viewing and a reduction in luminance, we also included a half-luminance binocular condition. Here, the same grid was presented to both eyes, but the luminance of the discs and grid in each eye was 25 and 8 cd/m^2, respectively. Some experiments used a stereo condition, which will be described at the relevant point.

A fixation cross appeared in the centre of the screen before each trial. After each trial, a masking stimulus of dynamic random noise was displayed for 1 s. On each trial, subjects were asked to rate the strength of the illusion from 0 to 5, with 0 meaning clear white discs with no scintillation and 5 meaning a clear black and white scintillation effect.

2.3 Subjects

All subjects had normal or corrected-to-normal vision. JCAR, JR, and CLS were authors; the others were naïve to the purpose of the experiments. Subjects were screened initially for whether they experienced scintillation. It has previously been reported that some people simply do not experience scintillation in this stimulus (VanRullen & Dong, 2003). In accordance with this, out of 20 people tested for this study, one was rejected because he always perceived the discs as solid white with no illusory black centres. This person is a laboratory member with normal vision, including stereopsis, and extensive experience of visual and stereo psychophysics. Prior to the experiments, the subjects viewed a fixed image of the grid with no time limit to establish a criterion for rating the experimental illusions. Experiments were carried out in accordance with the relevant institutional and national regulations and legislation and with the World Medical Association Helsinki Declaration as revised in October 2008.

3 Experiment 1: Scintillation is reduced by monocular viewing

3.1 Procedure

The aim of this experiment was to establish if the percept of scintillation is reduced when the stimulus is viewed monocularly, and if so, whether this depends on stimulus duration. Four different stimulus durations were used: 0.3, 0.5, 0.7, and 1 s. The four conditions were left eye monocular (L), right eye monocular (R), binocular (B), and binocular half-luminance (B/2). The binocular half-luminance stimulus was used to determine whether any difference between monocular and binocular was simply due to the greater luminance presented in the binocular stimulus and any consequent differences in brightness. In a single run, the 16 different stimuli were displayed 5 times each, randomly interleaved. Subjects were not informed of the purpose of the study nor that some of the stimuli were monocular. Subjects did at least 3 runs, resulting in at least 15 and on average 20 separate judgements for each stimulus.

3.2 Results and discussion

The results for 10 subjects are shown, averaged, in Figure 2. Schrauf et al. (2000) reported a modest decrease in scintillation strength as stimulus duration increased above 300 ms, whereas we find a modest increase. Both studies agree that the stimulus durations in this range have little effect on the illusion.

However, when it comes to binocular versus monocular viewing, our results conflict with an earlier study (Schrauf & Spillmann, 2000). Schrauf and Spillmann found no difference between binocular and monocular viewing (their Figure 4, zero disparity condition). In contrast, 9 out of our 10 subjects show a strong effect of binocular versus monocular viewing. One subject reported essentially no percept of scintillation when viewing the grid with his left eye, and his right eye and binocular results are very similar. Of the remaining nine subjects, eight clearly perceive less scintillation when viewing monocularly, while one shows the opposite effect. Nevertheless, 80% of our 10 subjects show a very strong reduction in scintillation with monocular viewing. Averaged across the 10 subjects (Figure 2), as Schrauf and Spillmann (2000) did for their 12 subjects in their Figure 4, we find a large and consistent difference between binocular and monocular viewing conditions, with binocular conditions producing a much stronger impression of scintillation.
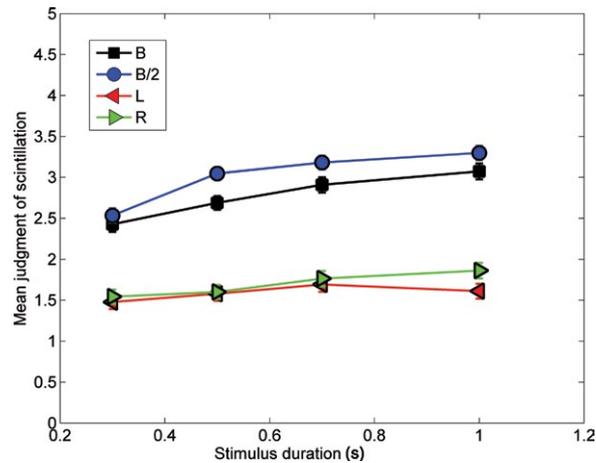
Figure 2. Results of Experiment 1 pooled across the 10 subjects. Each symbol represents the mean of 195 judgements by 10 subjects. Symbols show the different viewing conditions: B = binocular, B/2 = binocular with half the luminance, L = monocularly in the left eye, R = monocularly in the right eye. In each case, the standard error on the mean is smaller than the symbol.

To assess this, we performed a one-way ANOVA for each subject and stimulus duration individually, with viewing condition as the grouping factor. The effect of viewing condition was significant ($p < 0.05$) for all subjects and durations with the sole exception of subject JDL at 0.5 s. We also performed a three-way ANOVA test, with factors being viewing condition, subject identity, and stimulus duration. This analysis was performed using Matlab's ANOVAN function with the subject factor set to "random" and the duration factor to "continuous." All three factors—subject identity, stimulus duration, and viewing condition—were highly significant ($p < 0.01$). We also performed a two-way ANOVA after averaging judgements across subjects, with stimulus duration and viewing condition as the factors. Once again, both factors were highly significant. The effect of viewing condition cannot be due to the greater luminance or perceived brightness of the binocular stimulus, since scintillation was actually increased somewhat by halving the luminance of the binocular stimulus (compare B vs. B/2 conditions in Equation (1) and Figure 2).

We had obtained qualitatively similar results in a more informal pilot study, where subjects viewed a piece of paper printed with the scintillating grid, wearing glasses which occluded either the peripheral vision in both eyes (binocular condition) or all vision in one eye (monocular condition). This time subjects reported scintillation on a scale from 0 (no scintillation) to 10 (maximum scintillation). Of the 38 subjects, 20 reported more scintillation when viewing binocularly rather than monocularly with the dominant eye and only 9 reported more scintillation in the latter condition. The mean difference (binoc–dominant) was 1.6 with an SEM of 0.5.

It is not clear why we should have obtained such different results from Schrauf and Spillmann (2000). Differences in equipment may be a factor. Our binocular and monocular stimuli were presented randomly interleaved on a 3D monitor. In the monocular conditions, the other eye viewed a black screen of the same luminance as the background. Especially at the short stimulus durations, subjects cannot have been aware whether the stimulus was binocular or monocular. Schrauf and Spillmann (2000) used stimuli printed on paper with a laser printer and viewed in a stereoscope. In the monocular condition, they say images were presented through the stereoscope with the dominant eye viewing the grid stimulus, but it is not clear what the non-dominant eye viewed.

4 Experiment 2: Scintillation is reduced by relative disparity between discs and inducers

4.1 Procedure

Given our different results concerning binocular viewing at zero disparity, we decided to try and replicate Schrauf and Spillmann (2000)'s relative disparity experiment in full. They found that the percept of scintillation becomes weaker when a binocular disparity is introduced between the grid and the inducing discs. We interleaved five conditions: L and R monocular, as in Experiment 1, and three binocular conditions: B, binocular stimulus with zero disparity; S, binocular stimulus with relative
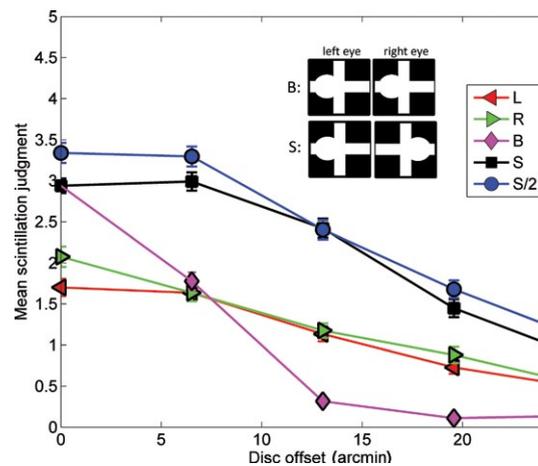
Figure 3. Results of Experiment 2, pooled across eight subjects. As shown in the inset, in the "B" condition, the same image was presented to the left and right eyes, with the horizontal axis corresponding to the offset between discs and intersections. In the "S" condition, the offset was in opposite directions in each eye, so that in the fused image, the discs appeared to lie directly in front of the intersections. S/2 was the same but with half the luminance. Error bars showing standard error on the mean are drawn, but are smaller than the symbols.

disparity ("stereoscopic" in Schrauf & Spillman's terminology), and S/2, the same as S but with half the luminance. The gridlines were presented in the same position on every trial, and the stimulus duration was 0.5 s. In the S conditions, the discs were shifted in opposite directions in the two eyes so as to introduce relative disparity between the discs and the grid, with the discs in front. In the monocular conditions L and R, only one eye's half-image was presented, while the other eye viewed a black screen. Condition S/2 controlled for any differences in perceived brightness between the L/R and B/S conditions. In the B condition, the discs were shifted in the same position in both eyes. This controlled for differences in scintillation due to the change in the monocular images. If the B and S conditions appeared equally scintillating, this would suggest that the stronger scintillation with binocular viewing was simply the sum of two monocular scintillations.

4.2 Results and discussion

The results are shown in Figure 3, averaged across subjects. Again, they are somewhat different from those of Schrauf and Spillmann (2000; their Figure 4). We have successfully replicated their main finding that the strength of scintillation reduces as relative disparity is introduced between the discs and the grid. In the monocular conditions, we agree with Schrauf and Spillmann that the scintillation becomes weaker as the discs are displaced from the gridlines. However, in our data, this decline is steeper for the zero-disparity binocular "B" condition than for the monocular "L" and "R" conditions. Thus, when
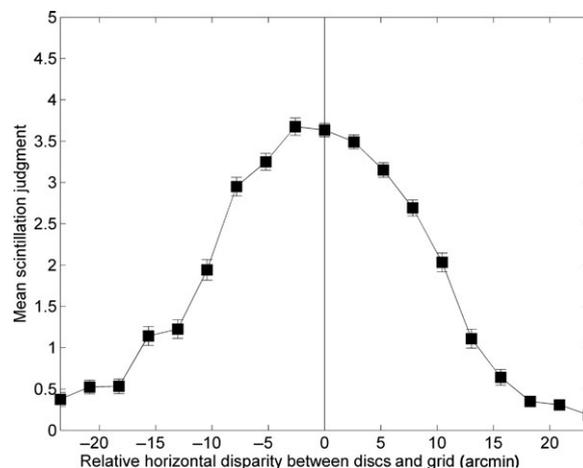

Figure 4. Results of Experiment 2 for eight subjects individually, stereoscopic S condition only, both crossed and uncrossed relative disparity. Data were collected independently from that presented in Figure 3.

the discs lie on the intersections, most of our subjects report more scintillation with binocular than with monocular viewing, replicating our Experiment 1 (one-way ANOVA for effect of viewing condition at zero disparity was significant ($p < 0.02$) for six of the eight subjects, not significant ($p > 0.2$) for IB and JDS). However, when the discs are offset from the intersections by more than about 1 disc radius (14 arcmin), most of our subjects report more scintillation with monocular viewing than binocular. Figure 4 of Schrauf and Spillmann (2000) shows the opposite behaviour. With zero offset, the authors find no difference between binocular and monocular viewing, but as the offset increases, scintillation becomes slightly stronger for binocular viewing.

We do agree with Schrauf and Spillmann on the critical B versus S comparison. Both studies find stronger scintillation in the S condition (discs hovering above intersections) than in the B conditions (discs offset from grid intersections). This indicates that the stronger depth percept with binocular viewing is not just the sum of two monocular contributions, but that there is a cyclopean contribution. As before, halving the luminance had little effect on the scintillation percept.

We also replicated Figure 2 of Schrauf and Spillman (2000), concerning the effect of crossed and uncrossed relative disparity between the discs and inducers (Figure 4). This confirms that it makes little difference whether the discs are presented in front of or behind the inducers.

5   Experiment 3: Absolute disparity has no consistent effect on scintillation

5.1   Procedure

One reason that the B condition in Experiment 2 appeared less scintillating than the monocular conditions could be because, in the monocular conditions, rivalry between the white discs in one eye and the black screen in the other eye tends to mimic scintillation. In the zero-disparity binocular condition, the discs are white in both eyes and therefore appear solid. To control for this effect, we compared the effect of absolute disparity, both horizontally and vertically.

In this experiment, the left and right eye's images were displaced in equal and opposite directions, either horizontally or vertically, so that the entire stimulus had a binocular disparity relative to the monitor. The stimulus duration was reduced to 200 ms to prevent vergence movements. Horizontal and vertical disparities were run in separate experiments. Within each experiment, different disparities were randomly interleaved. Monocular presentations in each eye were also randomly interleaved, using the half-images from a given disparity. In the figures, monocular results are plotted at this disparity, although clearly the monocular stimuli did not contain a disparity.

In this experiment, for disparities exceeding the disc radius of 14 arcmin, a disc in one eye always has black in the corresponding location in the other eye. If rivalry tended to increase scintillation, we would expect more scintillation to be perceived for large disparities than for zero disparity.

5.2   Results and discussion

The results are shown in Figures 5 and 6 (horizontal disparity) and Figures 7 and 8 (vertical disparity). First, we note that the difference between binocular and monocular conditions is less pronounced than in our previous experiments. This may be due to the shorter stimulus duration. Subject JME reported that all stimuli scintillated equally when viewed at 200 ms, although this subject had reported strong differences between binocular versus monocular at 300 ms in Experiment 1. Subjects JR and TW also did not report any differences between stimuli. These subjects did not perform Experiment 1, so it is not possible to compare their results at longer stimulus durations. Subject CFS did not show any difference between monocular and binocular viewing in the horizontal experiment (Figure 5), but did in the vertical disparity experiment (Figure 7). Since the zero-disparity stimuli were the same in both experiments, the different results may be to do with context: that is, the zero-disparity binocular stimulus appeared barely to scintillate in comparison with the diplopic large-vertical-disparity stimuli. Subject JDL is again the only one to report that scintillation is stronger when viewed monocularly than binocularly with zero disparity, although interestingly only when the binocular stimulus is presented near the screen plane (Figure 5). However, on average, the results confirm the results of Experiment 1. Most subjects report significantly more scintillation when viewing binocularly (Figures 6 and 8). The fact that this effect persists at a stimulus duration of 200 ms suggests that it is not due to some feature of vergence eye movements.

The absolute disparity of the stimulus has little consistent effect. Even whether the disparity is vertical or horizontal makes little consistent difference (compare Figure 6 with Figure 8). The stimuli with horizontal disparity mostly appeared fused, either in front of or behind the screen plane. In contrast,
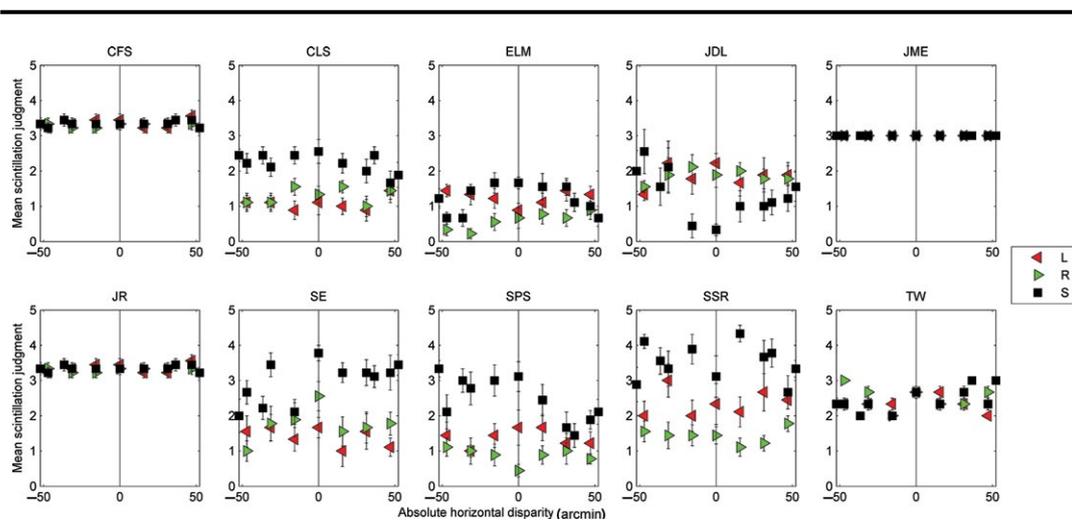
Figure 5. Experiment 2: effect of horizontal disparity, for 10 subjects individually. Details are as in Figure 1. Monocular stimuli were generated by showing one half-image from the image pair with the disparity at which they are plotted; clearly monocular stimuli did not contain disparity.

most of the stimuli with vertical disparity will have appeared diplopic, that is, two vertically offset grids were visible. The diplopic stimuli might be expected to produce a more lustrous appearance than the fused stimuli, since in the latter case the white discs appear solid, while in the former case they appear slightly unreal, since a white disc in one eye is paired with blackness in the other eye. However, any such difference evidently has little effect on perceived scintillation.

This suggests, first, that rivalry between a white disc in one eye and a black screen in the other eye is not usually reported as scintillation. Second, the lack of dependence on absolute disparity argues against a specific role for binocular mechanisms such as disparity-tuned neurons. We know that visual cortex contains many more neurons tuned to zero absolute disparity than to non-zero disparity. Thus, if these neurons helped boost the scintillation percept above the sum of monocular components, we would have expected the scintillation to be more powerful when the stimulus is presented with zero absolute disparity.

6 General discussion

Our results support the conclusion of Schrauf and Spillmann (2000) that the major component of the scintillating grid illusion arises before binocular combination, but that there is a minor contribution from binocular cortical mechanisms. These mechanisms seem to be tuned to cyclopean position rather
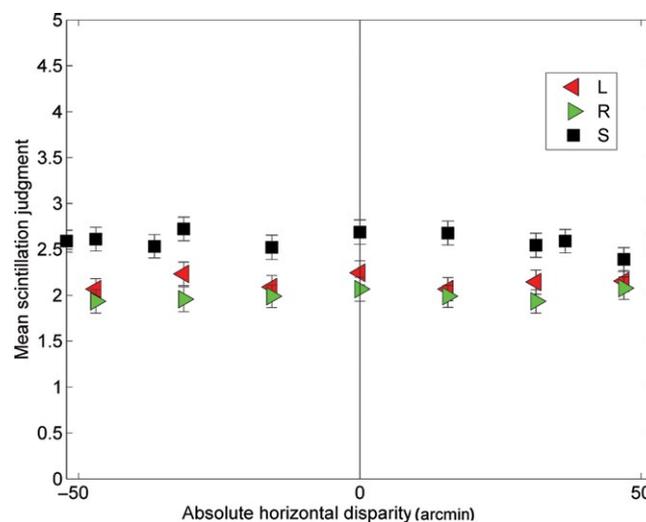

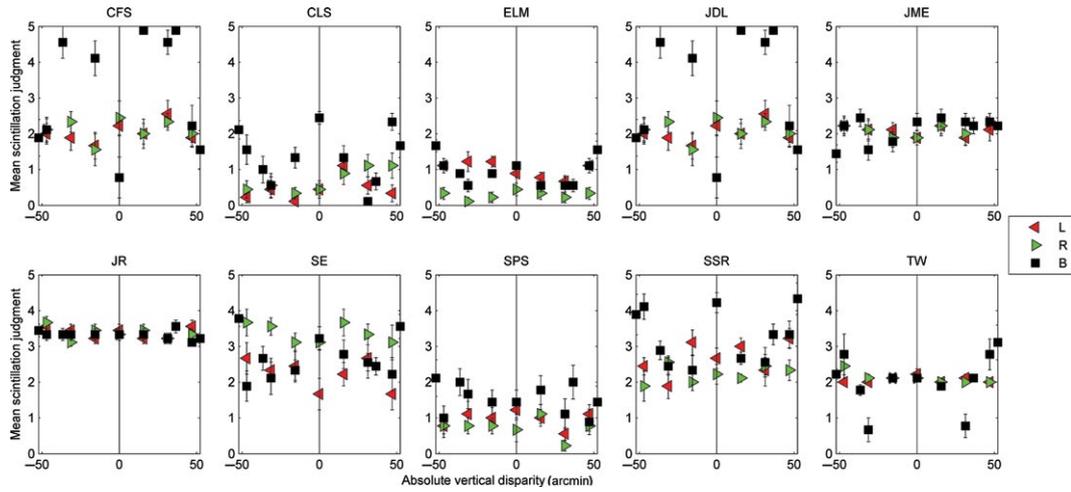**Figure 6.** Experiment 2: effect of horizontal disparity, pooled across 10 subjects.

Figure 7. Experiment 2: effect of vertical disparity, for 10 subjects individually. Details are as in Figure 1.

than to absolute disparity. Qualitatively, it seems that for most subjects, the scintillation perceived can be represented by something like the following equation:

$$S = LMw(x_{intL} - x_{discL}) + RMw(x_{intR} - x_{discR}) + LRBw(x_{intC} - x_{discC}) \tag{1}$$

where L and R are binary variables indicating which eye(s) the stimulus appears in: $L = 1$ if a grid stimulus is in the left eye, 0 otherwise, and similarly for R. The function $w(x)$ describes how rapidly the scintillation weakens as the disc moves off the grid intersection; it is an even function that peaks at 1 when its argument is 0. Thus, Equation (1) states that total scintillation is the sum of two monocular components, each with maximum strength M, and a binocular or cyclopean component with maximum strength B. In each component, a grid intersection at a particular location in the relevant "eye" (left, right, or cyclopean) will cause scintillation in a disc at a nearby location in that eye. x_{intE} and x_{discE} are the locations of a grid intersection and its nearest disc in eye E. E can be L, R, or C (cyclopean). The locations of the intersection in the cyclopean eye are

$$x_{intC} = (x_{intL} + x_{intR})/2$$

and similarly for x_{discC}. In this paper, we have investigated the effect of offsets between the discs and intersections which are the same in both eyes, x_{offset}; offsets that introduce relative disparity, d_{rel}; and absolute disparities, d_{abs}. The disc and intersection positions in Equation (1) can be expressed as

$$x_{discL} = x_{intL} + x_{offset} - d_{rel}/2,$$
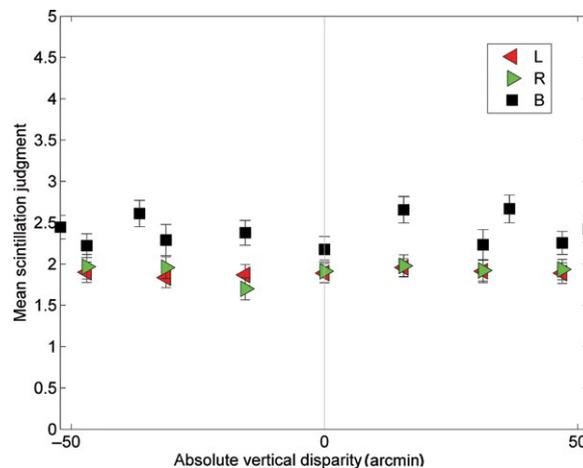$$x_{intR} = x_{intL} + d_{abs}, \ x_{discR} = x_{intR} + x_{offset} + d_{rel}/2.$$

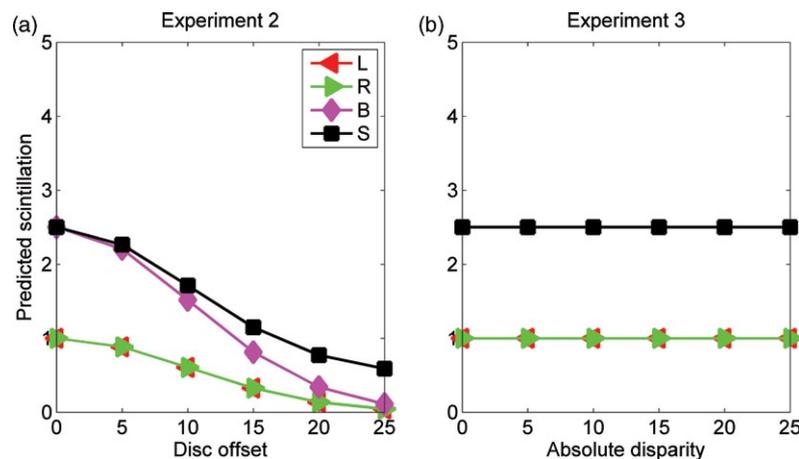**Figure 8.** Experiment 2: effect of vertical disparity, pooled across 10 subjects.

Figure 9. Behaviour of our descriptive model ([Equation (1)](#)) in Experiments 2 and 3. Writing X for the values on the horizontal axis in each case, the parameters are $M = 1$, $B = 0.5$; the function w is a Gaussian with mean 0 and standard deviation 10. (a) "L" refers to left monocular: $L = 1$, $R = 0$, $x_{offset} = X$, $d_{rel} = d_{abs} = 0$ (and analogously for "R"); "B" refers to binocular stimulus with zero disparity: $L = R = 1$, $x_{offset} = X$, $d_{rel} = d_{abs} = 0$; "S" refers to binocular stimulus with relative disparity: $L = R = 1$, $x_{offset} = 0$, $d_{rel} = 2X$, $d_{abs} = 0$. (b) "L" refers to left monocular: $L = 1$, $R = 0$, $x_{offset} = d_{rel} = 0$, $d_{abs} = X$ (and analogously for "R"); "S" indicates binocular stimulus with absolute disparity: $L = R = 1$, $x_{offset} = d_{rel} = 0$, $d_{abs} = X$.

Experiment 1 compared monocular versus binocular viewing of the basic scintillating grid stimulus, with $x_{offset} = d_{rel} = d_{abs} = 0$. For monocular viewing, then, [Equation (1)](#) says that the scintillation strength is $S = M$. For binocular viewing, it is $S = 2M + B$. That is, the enhancement in scintillation with binocular viewing is partly just a linear sum of the two eyes, and partly due to the activation of specifically binocular mechanisms.

[Figure 9](#) shows the model's behaviour for Experiments 2 and 3. The parameters are shown in the legend. The model successfully describes the main qualitative features of our data, specifically the decline in scintillation as the discs are moved away from the grid intersections, the increase in scintillation for the zero-disparity binocular stimulus over the monocular stimuli, the further increase for the stereoscopic stimulus when the discs are offset in opposite directions in the two eyes, and the lack of dependence on the absolute disparity of the stimulus. However, this model does not explain why, when the discs are offset from the intersections, observers perceive less scintillation with binocular viewing (compare pink diamonds in [Figure 3](#) with [Figure 9](#)). And of course it is purely descriptive; we have not attempted to implement [Equation (1)](#) with a plausible neuronal circuit. More work will need to be done in order to account for the interdependence of the scintillation percept on both disc position and binocularity.

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Christopher L. Smith was born and raised in the north-east of England and developed a love for science and the outdoors. He has been lucky enough to rock climb in America and across England as well as gain his degree in Physiological Sciences at Newcastle University. In the final year of his degree, Chris was fortunate enough to work in Dr Read's neuroscience laboratory in the ION institute at Newcastle.

Andrew D. Lucas was a high school student who worked on a six-week project researching the differences between monocular and binocular viewing of the scintillating grid illusion. Andrew will complete his A levels summer 2013.