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Vection depends on perceived surface properties

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Abstract

Optic flow provides important information for the perception of self-motion and can be generated by both diffuse and specular reflectance. Previous self-motion research using virtual environments has primarily considered the properties of diffuse optic flow, but not of specular flow. We used graphical simulations to examine the extent to which visually induced self-motion (vection) is robust against the variations in optic flow generated by different surface optics. We found that specular flow alone was capable of generating vection that was equivalent in strength to that generated by diffuse flow (Exp. 1). To test whether this specularly induced vection depends on midlevel visual processing, we measured vection strengths under conditions in which the luminance polarity of specular highlights was inverted. We found that inverting the luminance of specular reflections impaired vection strength, as compared with the vection generated by conditions with ecologically correct diffuse and/or specular flow (Exp. 2). We also found these variations in vection strength were correlated with the perceived relief heights of the surfaces depicted in the image sequences. These findings together suggest that vection can be induced by pure specular flow and that it requires processing beyond the computation of retinal motion velocities-most likely, processes involved in the recovery of 3-D surface shape.

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Vection depends on perceived surface properties

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Abstract

Optic flow provides important information for the perception of self-motion and can be generated by both diffuse and specular reflectance. Previous self-motion research using virtual environments has primarily considered properties of diffuse optic flow, but not specular flow. We used graphical simulations to examine the extent to which visually induced self-motion (vection) is robust against variations in optic flow generated by different surface optics. We found that specular flow alone was capable of generating vection that was equivalent in strength to that generated by diffuse flow (Experiment 1). To test whether this specularly-induced vection depends on mid-level visual processing, we measured vection strength under conditions where the luminance polarity of specular highlights was inverted. We found that inverting the luminance of specular reflections impaired vection strength compared with the vection generated by conditions with ecologically correct diffuse and/or specular flow (Experiment 2). We also found these variations in vection strength were correlated with the perceived relief height of surfaces depicted in image sequences. These findings together suggest that vection can be induced by pure specular flow, and requires processing beyond the computation of retinal motion velocities, and most likely, processes involved in the recovery of 3D surface shape.

Introduction

Optic flow is caused by the way that patterns of light, reflected by surrounding objects and surfaces towards our eyes, continually change as we move through the environment (Gibson, 1966). Visual percepts of self-motion depend on the visual system's ability to compute heading and velocity in three-dimensional (3D) space from these two-dimensional (2D) patterns of optic flow (see Lappe, Bremmer & van den Berg, 1999 for a review). The importance of optic flow for self-motion perception is evident in the fact that highly compelling illusions of self-motion can be induced in stationary observers by visual stimulation alone, traditionally known as *vection* (Dichgans & Brandt, 1978; for alternative definitions of this term see Palmisano, Allison, Schira & Barry, 2015). Most vection studies have used rather schematic dot motion displays to induce these illusions of self-motion. However, such displays do not fully capture the properties of the optic flow generated in the real world. Physical self-motions typically occur in environments consisting of extended/continuous surfaces. The global structure of the optic flow generated by self-motions in such environments will depend on surface properties of 3D shape, diffuse and specular reflectance. This study examines the role that these three different surface properties play in the visual perception of self-motion.

The reflectance of most opaque surfaces can be modelled using a bi-directional reflectance distribution function (BRDF). The intensity of diffuse reflectance depends not only on the albedo of the surface, but also on the angle of incident light relative to the surface normal. Because diffuse reflectance is independent of the observer's vantage point, light is distributed diffusely in all directions around a given surface normal according to a cosine function (see Figure 1A). Specular reflectance distributes light less broadly over a narrower lobe than diffuse reflectance. As a result, specular reflections are generated at locations in the image that correspond to surface regions with normals that bisect the angle formed between the illumination and viewing directions to the same surface point. Hence, specular reflections will tend to be less abundant in retinal images, compared with diffuse shading.

As shown in Figure 1 (B and C), these reflectance properties also have different consequences on the pattern of light reflected by surfaces as an observer moves through the visual environment. The global velocity of the optic flow generated by diffuse reflectance is approximately the inverse of the observer's velocity. In contradistinction, the specular reflectance of a surface is viewpoint dependent and tends to generate lower velocities of specular (relative to diffuse) flow. This is exemplified in the example of self-motion relative to a stationary point light source shown in Figure 1B and 1C. The diffusely shaded ground texture is seen to move eccentrically to a larger extent than the specular highlight. In the case of such flat surfaces, only the optic flow component generated by relative motion of the diffuse texture is informative about the true location of the observer within the environment. These diffuse and specular motions appear to be separable based on the relative differences in the velocity of optic flow they generate. However, this velocity cue is only useful for the special case of optic flow caused by purely flat surfaces.

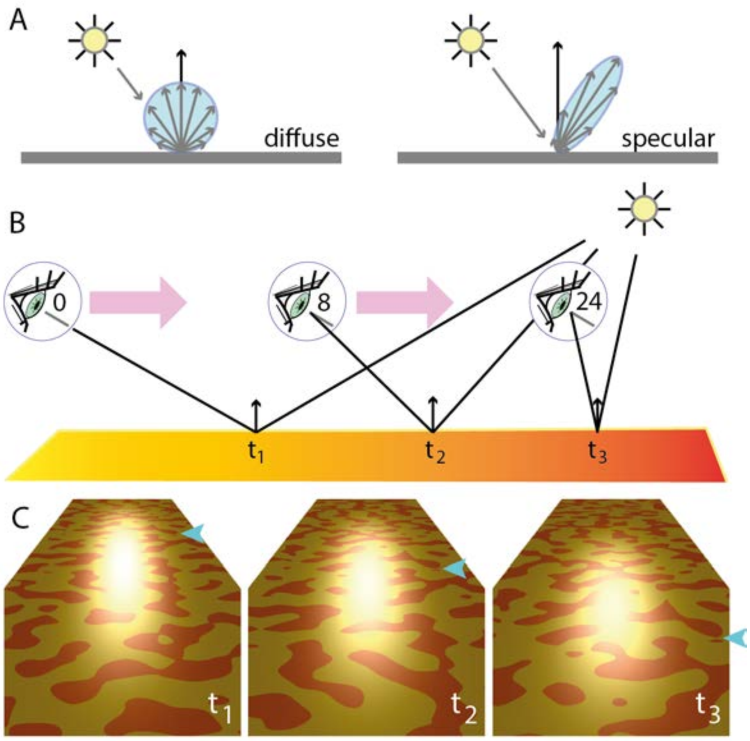

Figure 1. Optic flow generated by diffuse and specular reflectance during linear self-motion. A: Schematic showing the difference in the way light is distributed around surface normals in diffuse and specular reflectance. B: Profile showing the specular reflectance of a distal light source into the observer's eye translating forward in depth. Note that over time (t_1 to t_3) the optical displacement of a specular reflection away from foveal vision into the periphery is considerably smaller than the displacement of any finite point passed by the observer. C: Simulations showing the same concept from the perspective of the observer. Between times t_1 and t_2, the specular highlights generated by a distant light source move less in the image than diffuse points at the same initial location. The cyan arrow on the right of each frame shows the location of the same surface point in the image over time.

Most real-world surfaces are not perfectly flat, and tend to be uniform in albedo with 3D relief, and generate high-contrast diffuse and specular components that could (in principle) contribute differentially to vection. Previous studies have shown that vection is highly influenced by parameters of display size and density of moving contrasts (Brandt, Wist & Dichgans, 1975; Lestienne, Soechting & Berthoz, 1977). Brandt et al. (1975) found that rotary vection increased as a function of the number of moving display elements. This finding was also replicated for linear vection (Lestienne, Soechting & Berthoz, 1977), suggesting that vection generically depends on the density of moving contrasts in an optic flow display. This reported dependence of vection on the density of the optic flow field could underlie any potential effects of different surface properties on vection. For example, surface relief height influences the formations of diffuse and specular contrasts (Marlow, Kim and Anderson, 2012); increasing the relief height of surfaces tends to increase the abundance of diffuse contrasts, but tends to reduce the number of specular contrasts. This shows that diffuse and specular optic flow fields share complex interdependencies on 3D surface relief.

No previous research has systematically explored the potential effects of diffuse and specular optic flow on vection. Riecke et al. (2006) provided some evidence that dynamic scenes rendered with realistic surface properties can improve the experience of vection. Although they found that the simulation of more complex surface properties - including diffuse and specular reflectance - enhanced self-motion perception, some of these enhancements may have been due to increases in the size and contrast of the optic flows created by combining diffuse and specular components. Additionally, information concerning perceived 3D shape across displays with diffuse and specular reflectance was not determined. Perceived shape has been identified as an important factor in the perception of gloss (Marlow & Anderson, 2015), and possibly also vection. It is therefore unclear whether increases in perceived self-motion when combining diffuse and specular components are attributable only to variations in low-level parameters of optic flow or also to the mid-level recovery of surface properties.

The current study simulated self-motions relative to continuous surfaces to examine whether linear vection is differentially influenced by optic flow generated by diffuse and specular reflectance. The primary aim of this study was to ascertain whether specular optic flow contributes to the perception of self-motion, and the extent to which such percepts might differ from perceived self-motions generated by diffuse optic flow. We considered the role of three main surface attributes on the perception of self-motion: the surface's diffuse reflectance, and its specular reflectance. We also considered the role of perceived surface relief. Experiment 1 compared the vection induced by pure specular flow, pure diffuse flow and combined specular and diffused flow. Experiment 2 sought to ascertain whether specular highlights are processed independently of diffuse flow or merely contribute to the density of moving contrasts.

Experiment 1

Most previous studies have used simple computer generated 3D cloud (or dot motion) displays to generate optic flow simulating self-motion in depth (see Palmisano et al., 2011 for a review). These displays were not designed to simulate the reflectance properties of natural surfaces. While a few studies have examined vection induced by moving surfaces with complex reflectance profiles (e.g., using computer-generated imagery in Riecke et al., 2006; or real-world image sequences in Bubka and Bonato, 2010), they were not designed to identify the relative contributions of diffuse and specular shading to self-motion perception. By contrast, Experiment 1 used computer graphics to examine the independent effects of diffuse and specular optic flow components on vection in depth. We created custom software to generate a ground plane with relief, which allowed us to examine the effects of generating radial optic flow by specular-shading-only, diffuse-shading-only, or combined-specular-and-diffuse-shading.

Using this software, we performed some pilot test renderings and initial data collection (see Appendix A). We simulated self-motion in depth through a linear tunnel with relief and found that while specular only flow generated vection, its strength appeared to be inferior to that induced by diffuse only and combined optic flows. However, we also noticed that specular highlights tend to be constrained near the central region of the image, which appeared to be caused by the viewpoint dependence of specular reflectance. In contradistinction, diffuse shading was found to generate locally moving contrasts at all eccentricities in the image. Hence, the differences in display size and eccentricity of optic flow must be controlled between specular and diffuse conditions in order to undertake a fair psychophysical comparison of their vection-inducing potentials. In Experiment 1, we controlled eccentricity by introducing multiple light sources situated in depth.

If vection depends on low-level visual motion cues, then we might expect illusory self-motion to be weakest in the specular-only condition, as this condition generates lower net velocity retinal motion than the diffuse-only condition. Combining specular and diffuse flow might also reduce vection relative to the diffuse-only condition (as averaging the two flow components would generate a lower net velocity of retinal motion than diffuse-only flow, although it would still be greater than that in the specular-only condition). To alter the dynamics of radial specular flow, we imposed conditions where the lighting was stationary relative to the surface and moved relative to the observer (world-fixed), or was fixed relative to the observer and moved relative to the surface (observer-fixed). This was done to determine whether changing the rate of radial specular flow alters vection.

Materials and method

Observers

Six adult observers with normal or corrected-to-normal visual acuity participated in this experiment. All procedures were approved by the Human Research Ethics Advisory panel (HREA) at the University of New South Wales.

Stimuli

We generated an artificial 3D environment in the form of a curved ground plane using mesh functions provided in OpenGL libraries compiled in a custom application written in Microsoft Visual C++ 2010 Express running in the Window 8.1 operating environment on a Toshiba Satellite computer with an i5-4200U CPU and AMD Radeon R7 M260 graphics card. Stimuli were presented on a 21" Mitsubishi Diamond Pro 2070SB CRT monitor and viewed at a distance of approximately 45 cm. The display had a viewing range of approximately 49° horizontal and 37° vertical, similar to a recent vection study (Kim & Khuu, 2014). The luminance of the display's black and white points ranged between 0.5 cd/m^2 and 320 cd/m^2, though the working range for presenting optic flow was within an upper limit of approximately 40.0 cd/m^2. Background luminance in the periphery was adjusted using ambient lighting in specular only conditions to a nominal intensity of approximately 10.4 cd/m^2.

The ground plane was initially constructed in triangle strips with vertex positions falling on the circumference of a cylinder oriented in depth. The radius of each vertex in each ring was randomized by 5% of the radius to produce a rigid tunnel with relief. We then omitted the top half of the cylinder and scaled the radius by 50% in the vertical direction. This generated a ground-plane terrain with multi-scale curvature and bumpiness (see Figure 2).

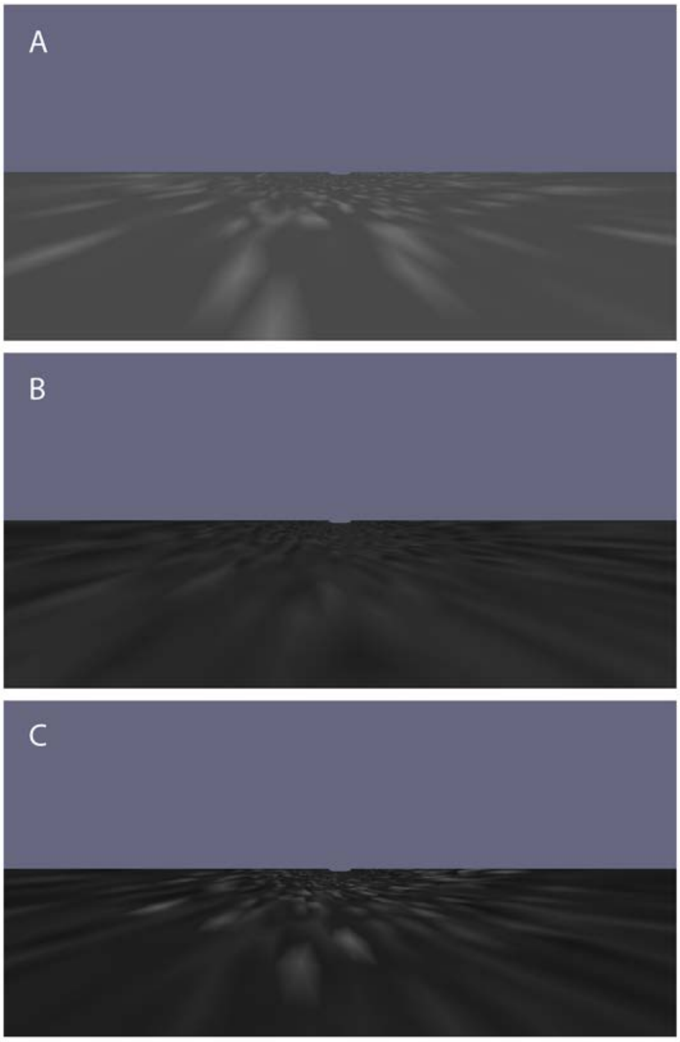

Figure 2. Layout of the flow field in the three main conditions. A: Specular flow only. B: Diffuse flow only. C: Combined flow generated by adding both diffuse and specular components together. Note that there are three light sources situated at equal intervals in depth, and that they moved relative to the observer (i.e., were world-fixed) on half the trials. Note that the local contrast of specular highlights is lower in specular only conditions (A), compared with combined (diffuse + specular) conditions (C).

We used a finite number of facets (strips constructed from triangles) distributed in depth to increase rendering performance. This was similar to the method of a previous study which simulated self-motion relative to 3D clouds of square objects that loomed in depth (Kim and Palmisano, 2008). All strips and vertex positions moved towards the observer on each frame. When a particular strip moved beyond the observer's viewpoint, it was deleted and a new strip was randomly generated and appended to the far end of the ground plane. This approach simulated smooth and continuous motion of the observer relative to a rigid ground-plane terrain that was seemingly unlimited in depth.

We rendered specular only, diffuse only, as well as combined specular and diffuse motion sequences. There were 3 light sources – separated by regular intervals (approximately every 3.5 metres or half the simulated distance in depth). This lighting was observer-centred for half of the trials; that is, the lighting moved with the observer. The remaining trials were world-centred and generated relative motion of lighting and the terrain relative to the observer. We increased the background luminance of displays containing pure specular flow to be comparable to displays containing diffuse shading flow.

Procedure

Observers were initially familiarised with the apparatus and shown a 3D cloud optic flow display, similar to those used in typical vection studies (identical to that used in a previous study by Kim et al., 2015). The cloud comprised blue square objects arranged in a spherical space simulated around the observer (approximately 3 m radius and 163, 840 objects ranging in optical size from 0.25 to 2.5 degrees with proximity to the observer). The luminance of the dots was 3.5 cd/m^2 against a black background of 0.11 cd/m^2). Observers were informed that they would be required to stare at the centre of similar flow fields, and concentrate on any experience of illusory self-motion. Following each self-motion display, observers were instructed to adjust a horizontal rating bar using the arrow keys to report the overall strength of vection they experienced for the trial. The rating scale ranged between 0 and 100 (0=completely stationary the whole time; 100=experienced self-motion indistinguishable from physical self-motion the whole time). Pressing the spacebar recorded the vection strength rating and commenced a 3 s delay in total darkness prior to the presentation of a subsequent trial. The motion display phase of each vection trial was 30 s in duration. Visual motion with two lighting conditions and three reflectance conditions were randomly presented in 30 s trials (2 x 3). Each observer performed at least two repeat blocks in a single experimental session lasting approximately 20 minutes.

Data analysis

Vection strength ratings were recorded to an ASCII file following each trial. We analysed vection strength data using a two-way repeated-measures ANOVA. We also computed local and global RMS contrast to determine the net number of moving contrasts in the three different display types.

Results and discussion

Figure 3 shows mean vection strength ratings for each of the three simulated reflectance conditions. Vection induced under different lighting conditions are represented by separate coloured bars, with world-fixed lighting shown in grey and observer-fixed lighting shown in blue. As can be seen, vection strength responses were fairly uniform across all conditions. The two-way ANOVA of vection strength data found no main effect of surface reflectance ($F_{2,10}$ = .34, p = .72) and no main effect of lighting condition ($F_{1,5}$ = 0.56, p = .49). There was also no significant interaction effect ($F_{2,10}$ = 1.20, p = .34).World-fixed and observer-fixed lighting generated similar vection, despite marked variations in the speed of the specular flow component in each condition. Thus, it would appear that the lighting was sufficient to induce compelling vection (even with specular flow alone), irrespective of its movement relative to the observer.

We also found that the vection induced by specular flow was as compelling as that induced by: (a) diffuse flow; and (b) combined flow. The uniformity in vection responses across these conditions cannot be explained by similarity in image contrast. In support of this view, we computed local and global display contrast across conditions, the means of which are shown in Figure 4. A one-way ANOVA found a significant main effect of display type on global image contrast ($F_{2,12}$ = 124, p < .00001). However, despite these large differences in global contrast (Figure 4B), the vection responses for the same conditions were statistically invariant. Additionally, we found no difference in vection between world-fixed and observer-fixed lighting conditions, where the rate of specular flow was varied. Rather than simply depending on the motion of contrasts per se, vection may have also depended on the distribution of these moving contrasts. The improved vection generated by specular flow in this experiment (compared to that induced by specular flow in our pilot study - see Appendix A) could potentially be explained by the similarity in eccentricity of the flow generated by both specular and diffuse components (Figure 4A). The next experiment attempted to determine whether vection depends on independent processing of specular and diffuse flows following initial source separation, or on their low-level motion signals.

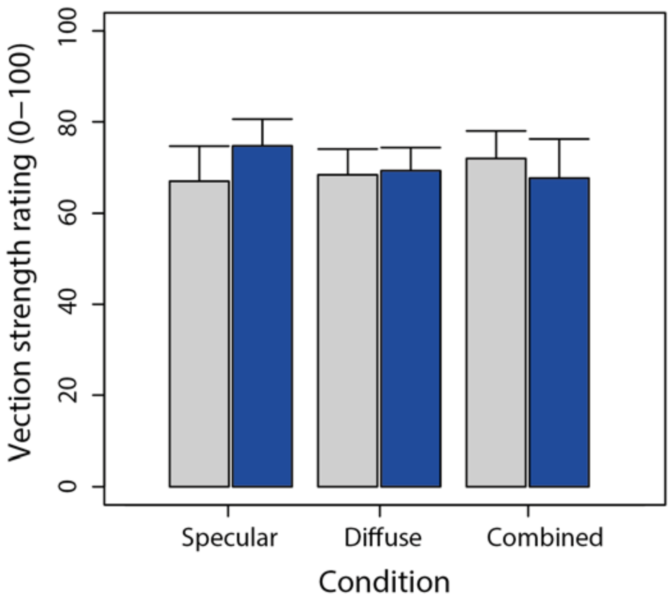

Figure 3. Mean vection strength ratings for different lighting and reflectance conditions. Means computed directly from vection strength ratings across all observers for each condition with specular shading only, diffuse shading only, or both diffuse and specular components combined. Vection strength for world-fixed lighting shown in grey, whereas vection for observer-fixed lighting are blue/dark. Error bars are standard error of the mean.

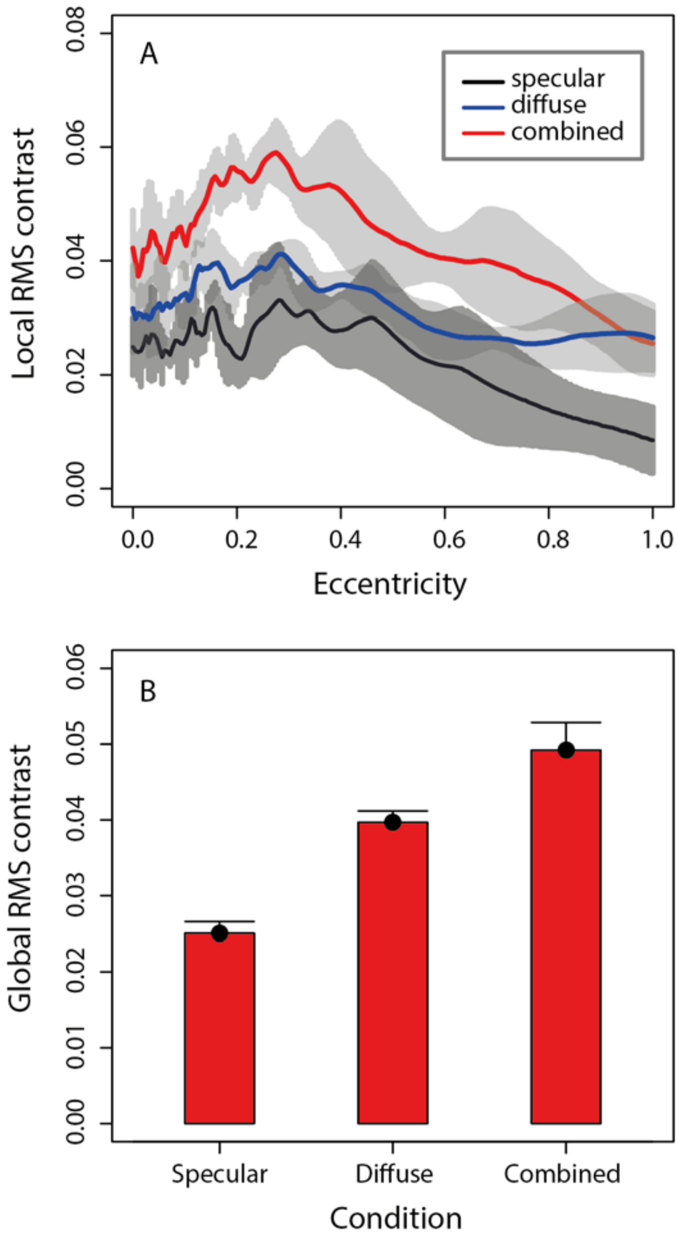

Figure 4. Root-mean-square (RMS) contrast for the ground plane. A: Local RMS contrast plotted as a function of eccentricity defined as vertical location in the image from centre. Separate curves show mean local contrast computed over five randomly selected frames from image sequences for each condition. Note that the contrast spans the full eccentricity of the display in all conditions. B: Global RMS contrast for the same images. Image contrast increases between specular and diffuse displays. Combining specular and diffuse components generates displays with the greatest overall contrast. Error bars are standard error of the mean.

Experiment 2

Experiment 1 showed that vection can be induced by specular flow alone. Indeed, under fair conditions, the vection induced by specular flow appears to have a comparable strength to that generated by diffuse flow. Vection was similar across the different lighting/reflectance conditions even though RMS contrast varied significantly. Therefore, it is possible that vection may not depend simply on the motion of display elements per se, but rather, on information about the motion of perceived surface 'bumps' relative to the observer. This would involve the mid-level visual inference of motion of rigid surface curvatures, rather than simply the motion of edge contrasts across the retina. This is feasible given that the perception of 3D surface relief depends on both diffuse and specular shading (Fleming et al., 2004). Indeed, the structure of specular shading is known to enhance the perceived relief of surfaces (Norman, Todd & Orban, 2004). Therefore, it is possible that the inferred movement of relief and not contrasts is important for vection.

It is likely that image highlights must first be attributed to specular reflectance prior to computing relief from their optic flow. Previous studies have shown strong dependencies of perceived shape and gloss on the structure of specular reflections; even small manipulations of specular shading have been shown to eliminate the perception of gloss (e.g., Beck & Prazdny, 1981; Todd et al., 2004; Anderson and Kim, 2009; Kim, Marlow & Anderson, 2011). For example, specular highlights are generated at regions of brighter diffuse shading and displacing them into darker regions decreases perceived gloss (Kim, Marlow & Anderson, 2011). In a similar way, inverting the luminance of specular highlights in an image eliminates perceived gloss (Marlow & Anderson, 2013). We performed similar luminance inversions of specular highlights, which should prevent the attribution of these image contrasts to specular reflections. This approach ensures that image contrast does not change; all the underlying spatial frequency distributions and net motion energies are roughly preserved as we are altering the local sign of the specular contrasts, but not the pattern of edges they generate. The manipulation should eliminate the experience of surface relief. If successful, one might predict that the decline in perceived relief should generate weaker vection than in conditions where specular reflections are physically correct.

Materials and Method

Observers

Eight adult observers with normal or corrected-to-normal visual acuity participated in this experiment. All procedures were approved by the Human Research Ethics Advisory panel (HREA) at the University of New South Wales.

Stimuli

Image sequences were pre-rendered using Blender 3D. This was done to increase the quality of renderings to be close to photo-realistic. Each grid comprised of 396,294 vertices was initially deformed using a pink noise height map. The camera was oriented to view the surface frontally so that 90% of the surface filled the field of view. A single collimated light source was used to illuminate the surface plane frontally, but angled slightly from above by 15 degrees. This ensured that specular flow conditions generated specular highlights that had a spatial distribution across the image that was similar in eccentricity to visual elements generated in diffuse only flow conditions.

Figure 5 shows sample image frames for each of the renderings conditions. Images in the top row are raw renderings with diffuse shading only, specular shading only or both in additive combination. The lower row shows images where the luminance profile is inverted. To ensure that the highlights would be maximally incompatible with adjacent shading in the combined case, we only inverted the luminance of the specular component relative the original diffuse shading profile (i.e., we did not invert the luminance of the entire image). For the diffuse only conditions, vivid surfaces with 3D relief are experienced in either the original or inverted polarity images. For the conditions with specular highlights, the surfaces appear as glossy surfaces with relief in the original renderings. However, the inverted specular highlights appear very differently and do not generate vivid experiences 3D surfaces.

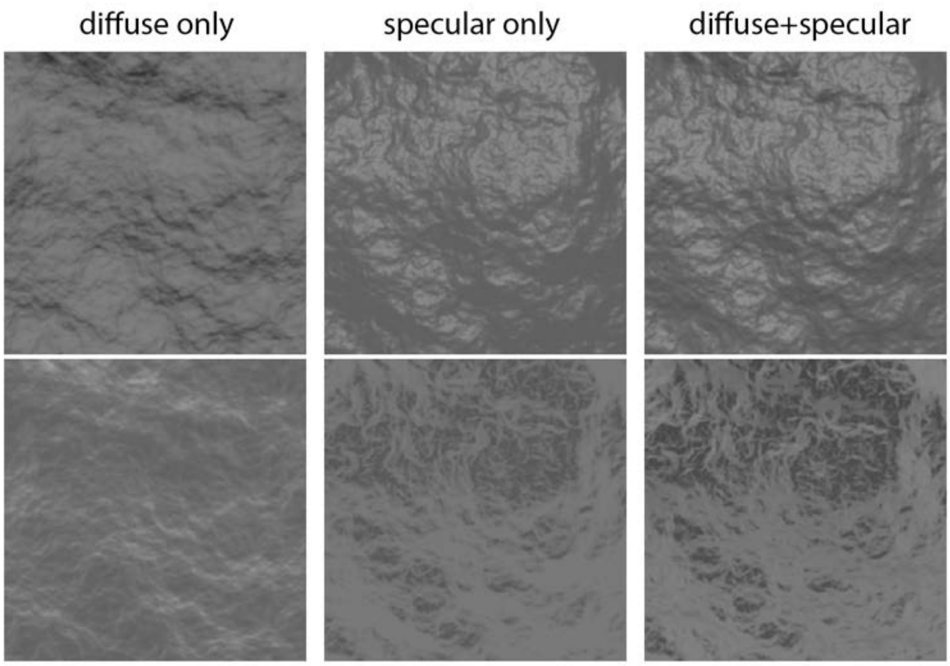

Figure 5. Sample image frames for each of the rendering conditions. Top row: Raw renderings with diffuse shading only, specular shading only or both in combination (diffuse+specular). Lower row: Same images, but with the luminance profile is inverted. Note that only the specular highlights were inverted in the combined case relative to the original diffuse component.

Procedure

We compared the strength of vection induced by the vertical motion of the surfaces relative to the observer. Movie sequences of vertical flow were presented to visually simulate downward self-motion. The observer performed 30 s trials with two repeats for all six test conditions (12 trials in total). All conditions were randomised within each block of repeat trials. A delay of approximately 10 s was provided between trials to allow observers to prepare for the subsequent trial. Observers indicated their vection strength experience for each trial using the same rating as in Experiment 1.

At the end of the vection testing, observers were shown short 8 s presentations of each flow condition once more, again in random order. They were instructed to rate the "overall bumpiness of the surfaces" they saw in these moving images. The same rating bar was used to record their perceived relief height estimates, which ranged from 0 (completely flat) to 1 (bumpy like raw granite). Responses were recorded and averaged.

Data analysis

We analysed vection strength and perceived relief height data using a two-way repeated-measures ANOVAs. Bonferroni-corrected t-tests were used where pairwise planned comparisons were required. A Pearson's product moment correlation was used to test for any relationship between vection strength and perceived relief height.

Results and discussion

Figure 6 shows bar charts for vection strength and perceived relief height for each of the three flow conditions (Matte/diffuse, specular and combined). Separate colours show responses to different specular and diffuse polarities: the original renderings (light), and negatives of the originals (dark). For the vection strength data, a two-way ANOVA found a significant main effect of rendering condition on vection strength ($F_{2,14} = 10.33$, $p < .005$). There was no significant main effect of image polarity ($F_{1,7} = .82$, $p = .78$), but there was a significant interaction effect between rendering condition and image polarity on vection strength ($F_{2,14} = 4.68$, $p < .05$). Bonferroni-corrected planned contrasts found a significant difference in vection between displays with inverted specular reflections and with original-polarity specular highlights ($p < .05$). There was no significant difference in vection between the two different polarities of purely diffuse shading flow ($p > .05$).

For the perceived relief height data, a two-way ANOVA found a significant main effect of rendering condition on perceived relief height ($F_{2,14} = 10.33$, $p < .005$). There was no significant main effect of image polarity on perceived relief height ($F_{1,7} = .20$, $p = .62$). However, there was a significant interaction effect between rendering condition and image polarity on perceived relief ($F_{2,14} = 16.22$, $p < .0005$). Bonferroni-corrected planned contrasts found a significant difference in perceived relief height between displays with inverted specular reflections compared with original-polarity specular highlights ($p < .05$). There was no significant difference in perceived relief between the two different polarities of purely diffuse shading flow ($p > .05$).

Given the similarity in the pattern of data between vection and perceived relief height, we investigated this relationship further. Figure 7 plots normalized vection strength as a function of perceived relief height across all observers. There was a significant positive correlation between normalized vection strength and perceived relief height of surfaces viewed ($r = 0.50$, $t_{46} = 3.87$, $p < .0005$). These results together indicate that vection is moderately correlated with perceived relief of surfaces. These results are consistent with the view that perceived relief depends on the appropriateness in the structure of specular reflections, relative to diffuse shading. Inverting the profile of diffuse shading did not significantly alter perceived relief height (and subsequent vection) due to the *bas relief* ambiguity. The possibility that vection depends on perceived relief is discussed further below in the general discussion.

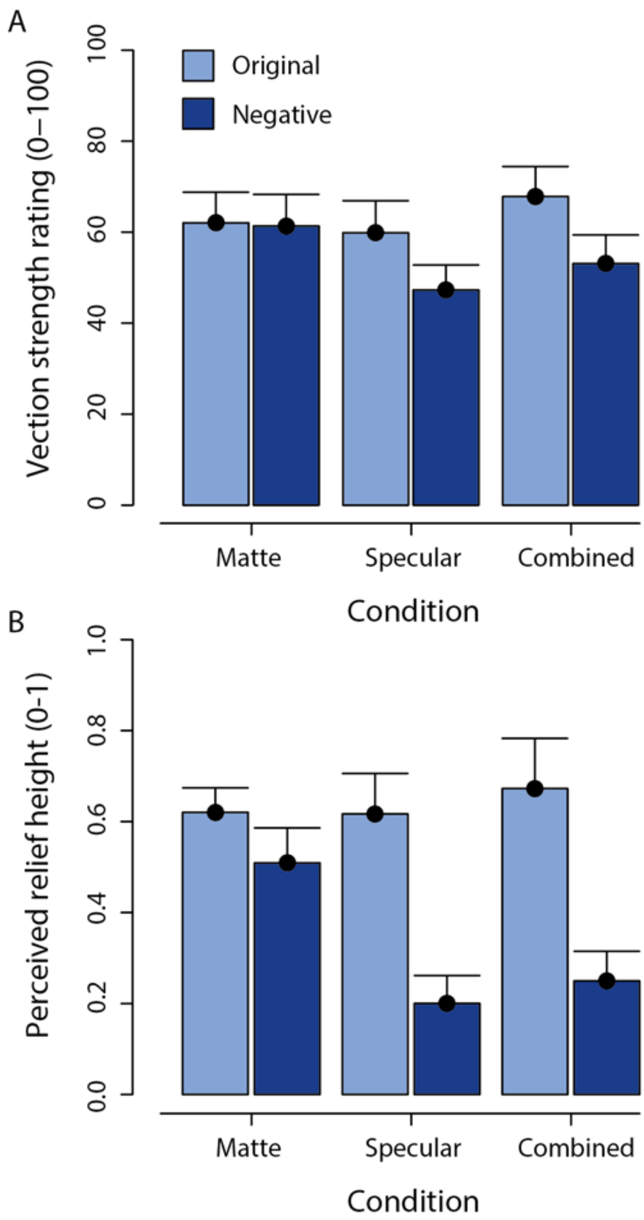

Figure 6. Psychophysical results of Experiment 2. A: Mean vection strength ratings for conditions with diffuse shading only (matte), specular shading only or both specular and diffuse combined. Separate bars show responses to raw renderings (light bars) and renderings with luminance inverted (dark bars). B: Mean perceived relief height for the same conditions. Error bars are standard errors of the mean.

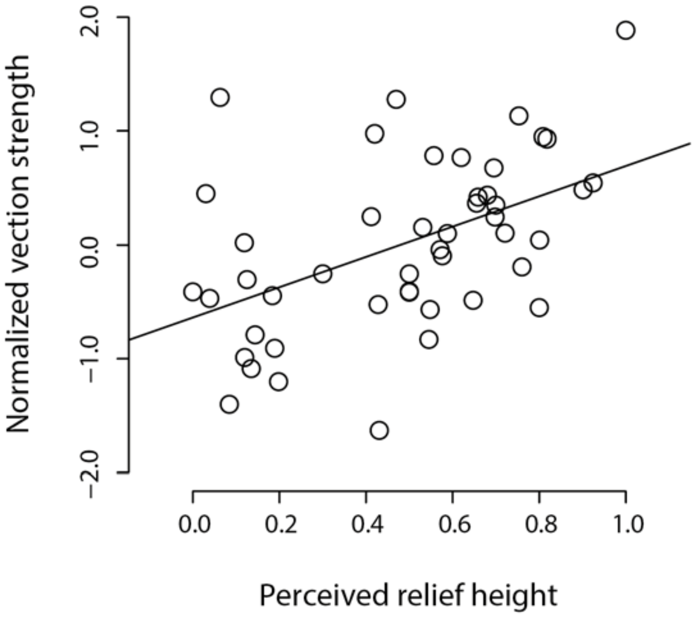

Figure 7. Normalised vection strength estimates plotted as a function of perceived relief height. Line of best fit superimposed. Values for perceived relief height range from 0.0 (completely flat) to 1.0 (very bumpy). Note the positive relationship between vection strength and perceived surface relief height (r = +0.49).

General discussion

We initially sought to determine whether specular optic flow is sufficient to generate compelling visual experiences of self-motion perception. We simulated self-motions relative to continuous surfaces and measured the strength of the vection that different displays induced. Experiment 1 demonstrated that specular flow alone was indeed sufficient to generate vection. Under the specific stimulus conditions of this experiment, the vection induced by specular-only flow was comparable to that induced by diffuse-only flow, and combining diffuse and specular components together did not significantly alter vection strength. Despite the uniformity in vection across diffuse and specular shading conditions, we found that RMS contrast varied considerably across these conditions. In Experiment 2, we found that inverting the luminance of specular highlights reduced vection strength, and this decline was correlated with perceived relief height. These findings together support the view that vection does depend (at least to some degree) on computations involved in the perception of surfaces and materials, rather than simply on low-level mechanisms.

The addition of the specular component to diffuse shading in Experiment 1 increased contrast of moving display elements (and possibly also their density), but a contrast-only explanation of the vection results does not appear valid. The combination of specular and diffuse components in Experiment 1 did not increase vection beyond that obtained with purely diffuse displays, suggesting that processing beyond low-level motion is important for vection. This is also supported by the finding that vection did not vary between conditions with observer-fixed and world-fixed lighting, where specular radial flow was have varied. Hence, despite these differences in overall image contrast and motion dynamics, we found no significant differences in vection strength across all lighting and reflectance conditions we tested (Experiment 1).

We also found that vection was correlated with the perceived relief height of surfaces (Experiment 2). Destroying the physical correctness of specular highlights reduced the perceived relief height of surfaces. It is possible that this decline might explain the associated decline in vection strength. If true, this would support the view that vection depends (at least in part) on the computation of moving surface curvatures, and not merely moving image contrasts. Previous studies have shown that the attribution of image highlights to specular reflectance depends on their luminance profile relative to surrounding shading (Beck & Prazdny, 1981; Todd et al., 2004; Anderson and Kim, 2009; Kim, Marlow & Anderson, 2012; Marlow & Anderson, 2013). In particular, Marlow and Anderson (2013) found that inverting the luminance profile of specular reflection decreased the experience of surface gloss. Similar declines were apparent in the current study, which were also accompanied by significant declines in perceived relief height. We propose that the accompanying decline in vection strength can be explained by the decline in perceived relief, which points to independent streams of visual motion processing of surface relief from specular and diffuse shading flow. Thus, the relative enhancement of vection in specular only conditions in Experiments 2 would appear to be best explained by visual computation of relief motion and not moving image contrasts per se.

Diffuse shading also appears to undergo mid-level processing, even though we found no effect of luminance inversion on either vection or perceived relief generated by purely diffuse flow. It is well known that perceived relief height of planar surfaces generates a *bas relief ambiguity*, whereby the experience of vivid relief in surfaces is generated by either upright or inverted images. The interpretation of relief tends to depend on an assumed light source from above prior, and has been shown to modulate mid-level estimates of surface properties (e.g., perceived lightness, see Kim, Marlow and Anderson, 2014). The absence of any effect of inversion on perceived relief height and vection in our study is consistent with this level of visual processing.

Previously, no studies had explicitly examined the effects of different surface optics on self-motion perception, but some researchers did consider the effects of lighting on vection induced by the motion of non-continuous surfaces. Nakamura et al. (2013) examined whether lighting could modulate the perception of self-motion generated by displays consisting of looming square objects. Their 3D cloud displays simulated self-motion in depth (i.e. radial optic flow). The lateral position of the light source was oscillated about the centre of the display to generate horizontal second-order transparent motion, based on the changing photometric energy reflected by the objects on either side of the display. They found that these dynamic orthogonal lighting oscillations reduced the strength of vection in depth, compared with conditions when the lighting position remained static. An earlier study showed that dynamic chromatic and achromatic modulation of the flow field also affected the strength of vection in depth (Nakamura et al., 2010). The findings from these previous studies suggest that the experience of self-motion is sensitive to source contamination of the optic flow field due to dynamic lighting properties. However, we did not find such effects in Experiment 1 when lighting moved co-linearly in the same direction as the observer; there was no difference between observer-fixed and world-fixed lighting on vection.

The findings obtained here with simulated surfaces offer new perspectives on interpreting the ecological characteristics of conventional vection stimuli typically comprised of random-dot or random-object motion displays. One recent study by Ogawa et al. (2014) did generate optic flow by displacing groups of identical tiles textured with images of static scenes (9 different tile types were examined – each depicting a single surface rendered with different material properties, including specularity). Although Ogawa and colleagues found that the group displacement of such images could induce compelling vection, the strength of this vection did not appear to depend on the material qualities of the surfaces rendered in these images. However, it is important to note that the surface properties of the tile images themselves did not contribute to the optic flow field as they normally would during their real viewpoint-dependent displacement. This particular limitation of that study prevented the specific analysis of the role of diffuse and specular flow cues in the perception of self-motion.

In contradistinction, we find here that surface optics do contribute differentially to vection, and that specular flow alone is sufficient to generate compelling visual experiences of self-motion perception. The findings of previous research suggest that perceived speed and vection are correlated (e.g., Kim & Palmisano, 2008). It is possible that the computation of surface relief might differentially affect perceived speed, which could be explored in future. It may also be worthwhile considering the role of realism of simulated displays (e.g., Riecke et al., 2006) and relative contributions of textural, specular, and diffuse flows to the computation of both surface properties and self-motion perception.

Appendix A

We performed an initial pilot test to verify that specular flow alone can induce vection. This test compared the strength of the vection induced by specular only flow, diffuse only flow and combined flow. We also examined differences in the eccentricity of moving contrasts generated by the diffuse and specular flow components, in order to determine whether such differences might need to be addressed in the main study.

Materials and method

Observers

Four adult observers with normal or corrected-to-normal visual acuity participated in the experiment. All procedures were approved by the Human Research Ethics Advisory panel (HREA) at the University of New South Wales.

Stimuli

The stimuli were similar to Experiment 1, except that a complete circular tunnel was rendered on each frame (rather than a ground plane). Relief was introduced using the same randomised vertex displacement. Background luminance in the periphery was adjusted using ambient lighting in specular only conditions to a nominal intensity of approximately 10.4 cd/m^2. This was done to ensure the highlights had similar intensity differences relative to the background across specular only and combined conditions (diffuse + specular).

Procedure

The procedures and briefing of observers were the same as in Experiment 1. Observers were instructed to provide vection strength ratings, but were not required to report vection onset latency during the presentation of each trial. In addition to analysing differences in vection strength using a one-way ANOVA, we computed the root-mean-square (RMS) image contrast locally along each row of pixels in frames sampled from each display condition. We also computed contrast globally across all pixels in the image. This allowed us to determine whether there were any potential image properties that could account for vection strength responses.

Results

Bar graphs in Figure A1 show means and standard errors for vection strength ratings across the three conditions with different simulated reflectance properties. A one-way ANOVA found a main effect of display type ($F_{2,6} = 7.11$, $p < .05$). Post-hoc t-tests found that raw vection was significantly stronger in the diffuse-only shading condition compared with the specular-only shading condition ($t_3 = 4.01$, $p < .05$), and combining both diffuse and specular components did not significantly alter raw vection strength compared with the vection generated by diffuse shading alone ($t_3 = 1.06$, $p = .37$).

Figure A2 shows the RMS image contrast of the different display conditions computed locally as a function of eccentricity (A) and globally across the entire image (B). While luminance-defined contrasts spread all the way from the centre of the display (0) out to its furthest edges (1.0) in conditions with diffuse only or combined shading, the spread was considerably narrower in specular only conditions (specular cut-off values: M = 0.37, SD = 0.07). Cut-off eccentricity values were significantly smaller for specular only conditions (M = 0.37, SD = 0.07) compared to the other display conditions ($t_4 = 18.81$, $p < .00001$). Additionally, a one-way ANOVA found a main effect of display type on global RMS contrast ($F_{2,12} = 713.3$, $p < .0001$).

The vection results cannot be explained by differences in *local* contrast of moving elements between the displays, as we increased the background luminance in specular only conditions to approximate their contrast in combined reflectance conditions. However, it is possible that the vection data could be explained by either the relatively low eccentricity or the global contrast of specular flow, compared with displays containing diffuse only or combined shading.

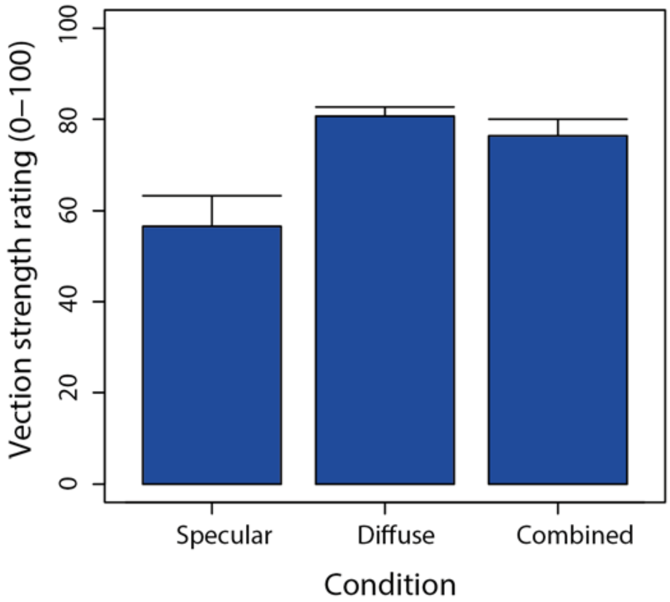

Figure A1. Mean vection strength ratings for the three reflectance conditions (Specular, Diffuse and Combined). Error bars are standard error of the mean.

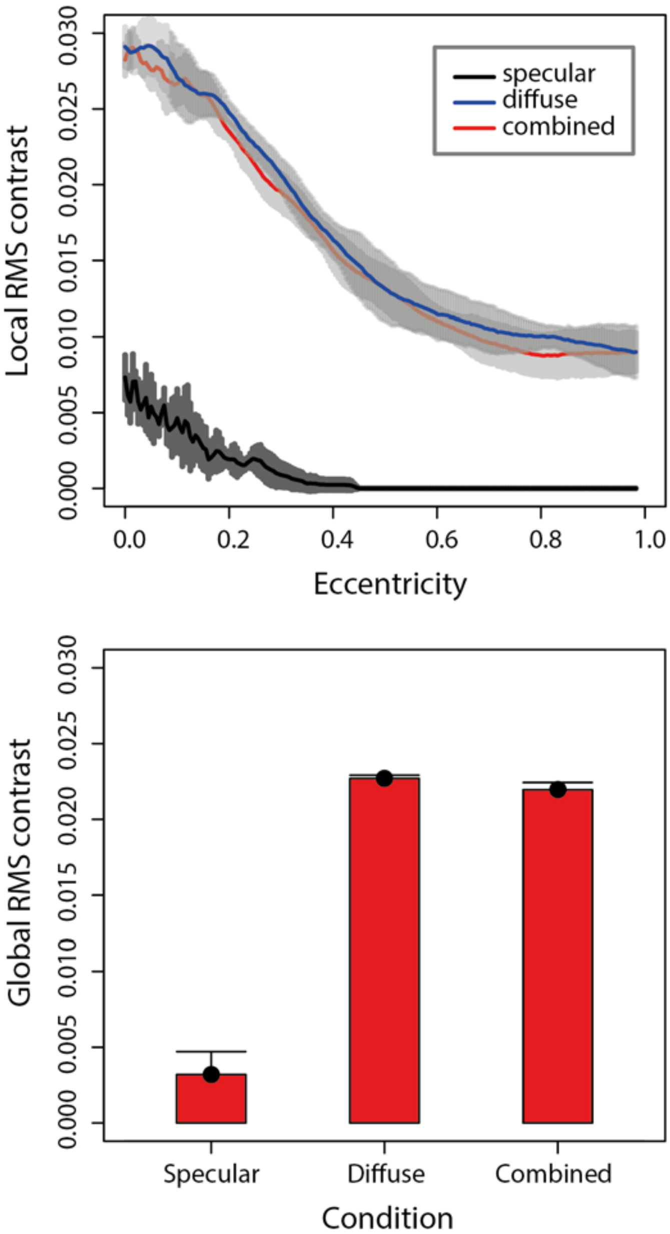

Figure A2. Root-mean-square (RMS) contrast for tunnel displays. A: Local RMS contrast computed over each row of pixels at different magnitudes of eccentricity, ranging from the centre of the display (0.0) to the lower-most edge of the display (1.0). Means were computed over five randomly selected frames from image sequences for each condition. B: Global RMS contrast computed over the entire image for the same images. Image contrast increases between specular and diffuse displays. Combining specular and diffuse components generates displays with the greatest overall contrast. Error bands and bars show standard deviations of the mean.

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