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Perceiving motion transparency in the absence of component direction differences

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ABSTRACT

The simultaneous perception of multiple motion components within the same region in the visual field is a difficult processing task, which can be solved by human observers for a range of transparently moving stimuli. We use transparently moving gratings to study this phenomenon psychophysically, focussing on configurations in which individual components move in the same direction and can only be discriminated by speed differences. We first demonstrate that the stimuli are perceived as transparent and then proceed to quantify how the strength of motion transparency changes while component grating parameters such as fundamental spatial frequency, speed and luminance are varied. The results were consistent with perception resolving a signal detection task of separating two superimposed global motion signals corresponding to each of the components. We also identify the importance of broadband stimuli containing edges, both for perceiving transparency with the same direction stimulus configuration, and for static transparency. The local density of edges has a direct influence on the strength of perceived transparency, suggesting that local motion detection at the edges of the stimuli, which is sensitive to speed differences, may be critical to solve the task. The work suggests that there may be a simultaneous retinotopic representation of the two speeds of motion analogous to that accomplished by the motion direction tuned neurons found across regions of visual cortex.

1. Introduction

Motion transparency is a well studied perceptual phenomenon which enables observers to make sense of visual scenes in which multiple motion signals belonging to different objects occur within the same region. In a world in which many objects in constant movement relative to each other exist at a range of distances from the observer, complex motion processing mechanisms can be ecologically useful. The computational problem with transparency perception lies in the process of integrating local motion signals into appropriate global motion signals and separating these signals into groups which reveal the structure of the visual scene. Sparse local motion signals can be integrated in a number of alternative ways, the simplest being vector summation which is seen in the perception of Random Dot Kinematograms (RDKs) with a distribution of directions and speeds (Watamaniuk & Duchon, 1992; Watamaniuk, Sekuler, & Williams, 1989). A vector summation used to obtain a global motion signal is single valued and would calculate the average direction of local vectors, which would not allow the system to identify separate transparently moving components. For successful transparency perception, the process of integrating local motion signals into a global motion percept must selectively integrate local signals while keeping different components sufficiently represented with separate global neural signals.

Motion transparency perception has been widely investigated psychophysically using a range of transparently moving stimuli, typically with superimposed components that differ in motion direction. RDKs have been used to demonstrate that separate transparently moving surfaces can be perceived with directional differences as small as 20–30° (Braddick, Wishart, & Curran, 2002; Mather & Moulden, 1980). Presenting RDKs to behaving Macaques in electrophysiological experiments, using similar direction discrimination tasks, led to the suggestion that the local motion is detected in primary visual cortex (*V*1) while the Middle Temporal region (MT) encodes the global motion within its population of neurons, with what appears to be a much more coarse directional resolution of 60–90° (Qian & Andersen, 1994; Treue, Hol, & Rauber, 2000). The mechanism through which this coarse representation in MT enables a finer perceptual separation is not fully understood. The percept of transparency produced by RDK components with direction differences can be disrupted so that flicker is perceived instead of transparency by locally pairing dots with the opposite direction of motions (Qian, Andersen, & Adelson, 1994). These observations support the idea of at least two levels of processing, a local and a global stage, and at the same time demonstrate that transparency perception requires that the dots are sufficiently

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sparsely located so that they are detected by separate local motion detectors. Columns of motion sensitive neurons tuned to different directions of motion and distributed throughout retinotopic *V*1 and MT of primates and humans (Hubel & Wiesel, 1977; Tootell, Dale, Sereno, & Malach, 1996) can therefore be thought of as simultaneously representing the multiple transparent components in their spiking patterns. Without directional differences between the components of the stimuli however, the known neural architecture could no longer be used to directly represent the transparent components in visual cortex.

Plaid patterns, which are a pair of oriented gratings moving in different directions, provide a bi-stable stimulus which can be perceived either as transparent components or as a coherently moving pattern (Adelson & Movshon, 1980). The probability of perceiving transparency as opposed to coherence for such a stimulus can be manipulated by changing the low level characteristics of its components. Psychophysical tasks involving plaids generally ask participants to subjectively report whether a stimulus is perceived as coherent or transparent. These experiments have established that the more different the plaid components are from each other in terms of parameters such as luminance, spatial frequency and velocity, the higher the probability of perceiving them as transparently moving (Adelson & Movshon, 1982; Welch, 1989). The perceived direction of motion for coherently moving plaids, when transparency is not perceived, is found to be best described under most circumstances by an intersection of constraints rule between the directional components, rather than the sum or average of local motion vectors (Adelson & Movshon, 1982). However, the intersection of constraints seems to break down, for example, when the contrasts of the components are very different, in which case there is a shift of the coherent direction towards the higher contrast component, or alternatively also when components have very different speeds (Stone, Watson, & Mulligan, 1990). The instances in which the intersection of constraints rule fails suggests a selective integration of local signals into a global motion percept where integration rules for perception are dependent on the components presented. This observed contrast dependence may be an effect of contrast on local motion detection, or possibly also the result of luminance and figural cues that have been found to be crucial for perceiving transparency in static transparent stimuli (Beck, Prazdny, & Ivry, 1984; Metelli, 1974). The perception of transparency in plaid patterns requires the perceptual grouping of motion signals arising from the different components. Such a grouping may take advantage of a variety of visual cues within an image, for example local motion signals or nonlinear luminance superposition cues associated with static transparency or figural cues, and there is little agreement about the nature of this cue combination (Lindsey & Todd, 1996; Stoner, Albright, & Ramachandran, 1990).

In the current study we investigate motion transparency in the absence of directional information, using a transparently moving stimulus made up of two linearly superimposed vertical luminance gratings moving along the horizontal direction. In such cases the perception of transparency requires a discrimination of component speeds for perceptual separation. The stimulus configuration should therefore give some insight into the perception of speed differences as well as the effect of lower level stimulus parameters on the percept. We initially establish with subjective psychophysical tasks that our stimuli can be perceived as transparent under certain conditions when components move in the same direction. This is consistent with an observation reported by Van Doorn and Koenderink (1982) in a task using temporally alternately presented moving white noise patterns that for high frequency alternation and larger speed differences (same direction), psychophysical observers reported two uniformly moving patterns, simultaneously moving in the same direction at different speeds. The observation of transparency was also made in psychophysical experiments with a pair of RDK components moving in the same direction at different speeds (Masson, Mestre, & Stone, 1999). The experiments by Masson et al. sought to characterise the thresholds for perceiving speed differences when RDK components were moving transparently when compared with thresholds for separate temporal intervals of moving RDKs with a range of temporal and speed parameters. Generally, thresholds for transparency perception were lowest for a broad range of average speed of 2–8 deg/s while for speed discrimination, an optimum sensitivity was measured at about 8 deg/s. Varying the interval time for the transparency detection and speed discrimination tasks suggested different temporal characteristics for the two tasks, with speed discrimination showing a shorter time constant of integration of 65 ms compared with 130 ms for the transparent stimulus under the conditions they tested. These time constants correspond to an integration of local motion signals requiring about 100 ms and 400 ms, respectively, for the two tasks. In psychophysical experiments containing three transparent components in total, two moving with the same speed in different directions and a third with a different speed and direction, RDK transparency was observed under certain parametric conditions where the speed difference between the third and the first two was sufficiently large (Greenwood & Edwards, 2006). This experiment was used to demonstrate that motion transparency perception can be considered a signal detection task, where detection limits can be extended beyond the typical two components by increasing the signal to noise ratio. The three components were thought to be simultaneously perceived under the condition where the two speeds in the stimulus were sufficiently different from each other. This was achieved by using a speed difference between the components of 8 deg/s, a value of speed difference thought to activate independent speed detection channels (Edwards, Badcock, & Smith, 1998; Snowden, 1990). The range of speed differences over which RDKs are seen to have an optimal sensitivity in the Masson et al. study is below the limit thought to be required for completely independent speed detection. This makes the case for a single continuous speed tuned system as previously suggested by adaptation experiments (Van Boxtel, Van Ee, & Erkelens, 2006) instead of a separate fast and slow speed tuned mechanism.

We attempt to make more quantitative measures of the transparency and characterise the effect of speed difference and other low level stimulus parameters on perception. We use a comparison task in the second set of experiments to estimate the strength of perceived transparency in this same direction configuration. This allows us to make inferences about the perception of motion transparency which go beyond an assumption widely made until now, that direction differences are critical for motion transparency. The work here implies that just as component directions in transparently moving stimuli with directional differences are thought to be simultaneously represented in lower visual cortex, there should be an analogue for representing multiple speeds.

2. Experiment 1: subjective estimates of transparency strength

2.1. Stimuli

The subjective tasks were used to establish, by directly asking participants in psychophysical presentations, whether a range of stimuli appeared differentially transparent. Transparently moving stimuli were made up of two vertical gratings each of them set independently to a particular speed, fundamental spatial frequency and luminance. These gratings were superimposed linearly and then adjusted to use the full 8-bit greyscale with a luminance range of 0.5–72 cd/m^2. We used different grating types: pure sine waves, square waves, triangular waves, periodic lines and various harmonic gratings. For each of these grating types, we created a transparently moving stimulus in which the two components moved in the same direction, one with a slower speed of typically 3.2 deg/s and the second with a faster speed of 6.4 deg/s. Whereas sine waves by definition are narrowband with a single spatial frequency, defined along the x-axis (Eq. (1)), the rest were all broadband stimuli with different amplitude and phase relationships between their frequency components. Square and triangular waveforms both have a harmonic structure, with infinite odd harmonics but substantially different phase relationships between these harmonics (see Appendix A). We created a continuum between narrowband and broadband waveforms to generate transparently moving 'square harmonic gratings' or 'triangular harmonic gratings' by manipulating the number of harmonics, n, contributing to the periodic pattern, as given by Eqs. (2) and (3). These stimuli define a monotonic scale from narrowband when $n = 1$ becoming increasingly broadband as n increases.

$$\mathrm{Sine}(x) = A_1 \sin(k_1 x + \omega_1 t) + A_2 \sin(k_2 x + \omega_2 t) \tag{1}$$

$$\mathrm{Square}(x) = \frac{4}{\pi}\sum_{a=1}^{n}\left(\frac{A_1}{(2a-1)}\sin((2a-1)(k_1 x + \omega_1 t)) + \frac{A_2}{(2a-1)}\sin((2a-1)(k_2 x + \omega_2 t))\right) \tag{2}$$

$$\mathrm{Triangular}(x) = \frac{8}{\pi^2}\sum_{a=1}^{n}(-1)^{a-1}\left(\frac{A_1}{(2a-1)^2}\sin((2a-1)(k_1 x + \omega_1 t)) + \frac{A_2}{(2a-1)^2}\sin((2a-1)(k_2 x + \omega_2 t))\right) \tag{3}$$

In Eq. (1)–(3), A_1 and A_2 are the amplitudes of the two components, k_1 and k_2 are their fundamental spatial frequencies and ω_1 and ω_2 their temporal frequencies. The speed of each component is therefore determined by the ratio ω/k. The index a is used to generate the odd harmonics, and n is the total number of odd harmonics. When $n \to \infty$, Eqs. (2) and (3) generate square and triangular waves, respectively. We tested the triangular and square wave harmonic gratings given by Eq. (2) and (3) systematically while varying n. As a control stimulus, we also generated stimuli with the harmonic phase relationships of triangular waves but the $1/f$ amplitude dependence of the square waves. These resulted in what looked like triangular harmonics (at low n) with exaggerated amplitude of maxima and minima, given by Eq. (4).

$$\mathrm{Control.tri}(x) = \frac{4}{\pi}\sum_{a=1}^{n}(-1)^{a-1}\left(\frac{A_1}{(2a-1)}\sin((2a-1)(k_1 x + \omega_1 t)) + \frac{A_2}{(2a-1)}\sin((2a-1)(k_2 x + \omega_2 t))\right) \tag{4}$$

As an alternative vertical grating type, we also tested periodic line gratings. These are periodic vertical lines one pixel wide, which had a maximum luminance of 72 cd/m^2 on a grey background of 36 cd/m^2. For these gratings, it was not possible to construct a stimulus in which the richness of the Fourier spectra was manipulated simply by changing the number of harmonics. The speed difference between the transparently moving components was the parameter varied. The slower moving grating was set at a speed of 3.2 deg/s and the faster grating had its speed systematically set at one of seven values between 4 deg/s and 8.8 deg/s.

2.2. Methods

Stimuli were generated using a Cambridge Research Systems Visage visual stimulus generator with a 19′ Eizo flexiscan T662-T CRT display. The monitor was set at a refresh rate of 60 Hz and participants used a chinrest placed 57 cm from the screen. Transparent stimuli were presented in the central visual field in single intervals of 750 ms, within a square region located at the centre of the screen whose sides subtended a visual angle of 9.5°. Participants were asked to keep their eyes fixated on the centre of the stimulus on a small round fixation spot during presentation to minimise any effects of eye movements. The stimuli were generated using bespoke routines written in Visual C++ and run on a single core Windows XP PC. When both components of transparently moving stimuli were moving in the same direction, this direction was reversed after each presentation to reduce adaptation effects.

In each block, the participant was asked to rate the perceived transparency strength of each presentation on a subjective scale between one and five, one being not transparent and five being strongly transparent. Each block of 70 trials contained seven different stimuli of a given parameter setting, each selected for display in random order 10 times. The definition of transparency given to participants was the vividness of perceiving two separate layers sliding across each other in the image, without including any explicit criterion for the separation and ordering of depth planes. In each trial the participant's subjective rating was recorded by moving the mouse to an appropriate box on the screen and clicking the left mouse button. The experiments were done under ambient light conditions in a quiet laboratory. There were ten unpaid participants in total used for all the reported experiments, with normal or corrected to normal vision, four of whom had some knowledge of the aim of the studies (including the first author) and six of whom remained naïve about the aims of the study throughout. All participants gave written consent and the study was approved by the Royal Holloway University of London ethics committee. After each set of subjective experiments, naïve participants were asked to describe their percept and also to comment on the ease with which they performed the task. We used a large number of participants throughout the work presented here to demonstrate that the experimental tasks could be used for almost any psychophysical observer and where subsets of the group were assigned to different conditions, this was done on a random basis to limit the total observation time we requested of each of the participants.

We used this subjective method to explore what stimulus types and configurations were perceived as transparent, as well as what low level stimulus characteristics showed a gradient of perceived transparency strength as they were varied systematically. In initial piloting, we found that participants tended to try and use the full response range of one to five even in blocks which they retrospectively reported to appear as largely non-transparent. This is a confound of the subjective measurements, but the gradient of these responses is a useful indicator of the trends even if the scale does not accurately quantify the trends. This section also served to initially explore the role of the Fourier spectra (both amplitude and phase) for the perception of transparency.

2.3. Results

Square harmonic gratings were perceived by all participants as transparent and the strength of perceived transparency increased systematically with the number of odd harmonics contributing to the gratings, as shown in Fig. 1a. For triangular wave gratings, participants consistently reported after the task that the stimulus was perceived as non-transparent or very difficult to perceive two separate motions and varying the number of harmonics showed little effect on the results of percept strength (Fig. 1b) except a slight difference where the stimulus had just two harmonics. To explore whether the phase relationships between the harmonics could be the cause of the perceptual difference between the triangular and square harmonic gratings, we used the control $1/f$ harmonic triangular gratings and found that they showed a lower gradient of perceived transparency strength than the square wave gratings but

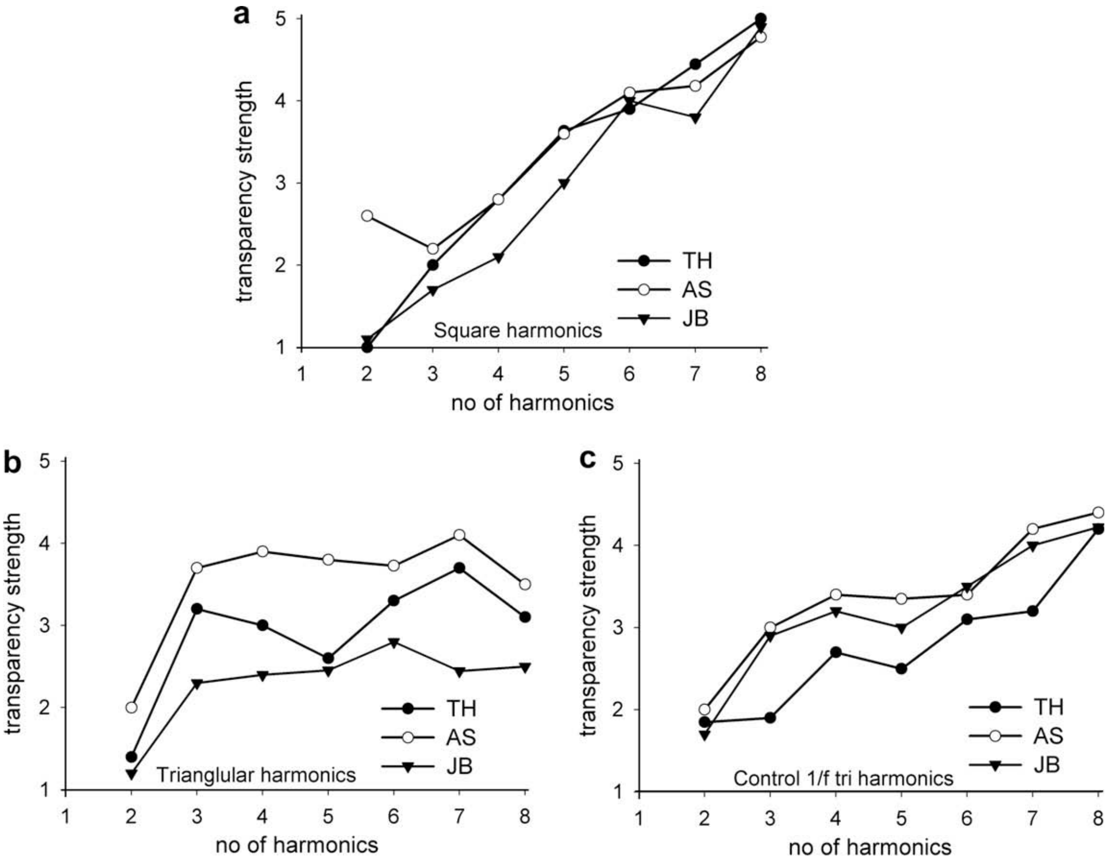

Fig. 1. Subjective ratings of perceived transparency for two harmonic gratings moving in the same direction at different speeds, with the number of odd harmonics, *n*, varied from 2 to 8. (a) Square harmonic gratings show an increase in reported percept strength with number of odd harmonics. (b) Triangle harmonic gratings show no systematic trend, and were reported to be perceived as completely non-transparent. (c) Control 1/*f* triangular harmonic gratings show a weaker and less consistent effect of harmonics on transparency strength than (a), and seem to show some slight increase in transparency with *n*.

generally seemed to show a stronger percept as the number of harmonics was increased (Fig. 1c). The subjective results shown were obtained for three naïve participants. The gradient of perceived transparency strength seen for the control stimulus was probably connected to the perception of the lines which appear at the maxima and minima of the distorted triangles as *n* is increased. This transition to periodic line stimuli limits the range of *n* over which the 1/*f* stimuli can reasonably be thought of as a control stimulus.

Periodic lines moving in the same direction at different speeds were used to establish the relationship between the speed difference and perceived transparency strength between the two components. As shown in Fig. 2, these stimuli appeared non-transparent when components differed little in speed, but were increasingly perceived as transparent when the speed difference between the two components was increased.

2.4. Discussion

For both square harmonic gratings and periodic line gratings, under certain stimulus conditions, grating pairs moving in the same direction at different speeds were consistently reported by participants to be perceived as containing two separate perceivable motions. When varying the number of odd harmonics which make up the square harmonic gratings, all participants found the strength of the percept of transparency to be related to the richness of the stimulus Fourier spectrum (see Fig. 1a). A broadband Fourier spectrum therefore appears to be one of the critical stimulus conditions for perceiving motion transparency under this same direction configuration. Stimulus harmonic phase relationships which result in edges are also demonstrated to be crucial for the percept of transparency. We think it unlikely that more broadband stimuli consistently appeared as more strongly transparent purely because of the presence of higher frequency components. Though this possibility can only be ruled out by testing stimuli in which lower frequencies are systematically excluded. If it was the case

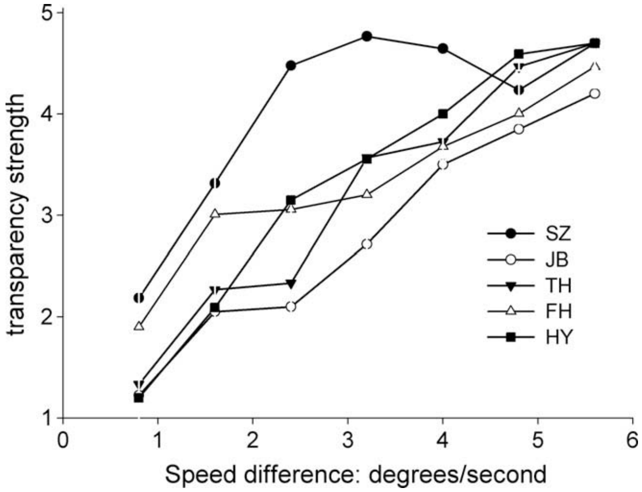

Fig. 2. Subjective ratings of perceived transparency strength for line gratings as function of the speed difference between the transparently moving components. At low speed differences these stimuli are perceived as less transparent than at higher speed differences for all participants.

that the presence of higher frequencies alone in the broadband stimuli aided in transparency perception, and not the fact that the stimulus becomes increasingly broadband, high frequency narrowband paired grating stimuli may be expected to appear more strongly transparent than similar narrowband stimuli of much lower frequency. In fact, two such sets of narrowband stimuli are both perceived as beats (Badcock & Derrington, 1985) rather than transparent. The broadband stimuli also contain more stimulus information than narrowband stimuli and would contain more information which corresponds to a stronger signal for any multi-scale detection mechanism.

Triangular wave gratings, which show an even phase locking between harmonics, were not perceived to be transparently moving and participants reported difficulties in performing tasks containing the stimulus (see Fig. 1b). When even phased control stimuli with the harmonic amplitudes matched to those of square gratings ($1/f$ dependence) were used, given by Eq. (4), the stimuli were again reported as largely non-transparent for the first few harmonics, but appeared to be perceived as transparent (Fig. 1c) when composed of a higher number of odd harmonics – in these cases the tips of the triangles began to appear as lines. In the limit of $n \to \infty$ in Eq. (4), the stimulus tends to become periodic lines with alternating polarity (black and then white). The results of the subjective task shown in Fig. 2 demonstrated that speed difference between the moving components was another critical factor for the percept under the current configuration. In the complete absence of a speed difference, the percept was annihilated.

The gradients of subjective responses reported in Figs. 1a and 2 demonstrate that the percept appeared to increase in strength along the tested axes i.e. number of harmonics and speed difference, respectively. We infer from these initial results the importance of both the Fourier spectra as well as speed difference for the percept, without being able to quantify these effects or compare them between participants. We observed in these tasks that participants typically adjusted their responses to use the full range of 1–5 where possible. A more quantitative method is therefore required to obtain deeper insights into the solving of the task behind the perception of motion transparency and this was sought in the next section.

3. Experiment 2: quantitative measures of transparency strength

3.1. Stimuli and methods

We used the observations from experiment 1 as the basis for developing a two-interval forced-choice task. The subjective task employed in experiment 1 enabled us to identify critical stimulus parameters which differentially modulated the strength of perceived transparency, and thus to acquire sets of stimuli which vary in a single parameter that can be used as a reference scale for perceived transparency strength. In the two-interval comparison task, each individual stimulus interval is similar to those described in Section 2.2. One interval contains the test stimulus for which we want to estimate perceived transparency strength, and the other contains one stimulus from the reference set, presented in a randomised order. The aim of these experiments was to measure the perceived transparency strength of any given test stimulus in terms of the equivalent perceived transparency along the reference scale stimuli. It therefore exploits the observation that a gradient of perceived transparency strength is observed along the reference scale parameter and values of equivalent perceived transparency in between the discreet reference scale points are estimated by fitting a psychometric curve. In one experimental block a total of 250 two-interval trials were presented according to the method of constant stimuli; in each individual trial one of five transparently moving reference scale stimuli was combined with one of five transparently moving test stimuli; each stimulus combination was presented 10 times, in a random order.

Each reference scale stimulus was made up of two linearly superimposed gratings, one moving slowly and the other moving faster, both in the same direction. For the experiments with square harmonic gratings, the speeds of the two components of the reference stimulus were fixed at 3.2 deg/s and 6.4 deg/s, respectively. The grating spatial frequencies were fixed at 0.263 cycles per degree and the gratings had the same luminance –36 cd/m^2. The perceived transparency of the five reference stimuli was manipulated by varying the number of harmonic components contributing to the two superimposed gratings, so that the stimulus with three harmonics appeared to be much less transparent than the stimulus with seven harmonics. For the experiments with periodic line stimuli, the speed difference was used to generate a reference scale. One grating of the reference stimulus set had a fixed speed of 3.2 deg/s, while the other grating was assigned a speed at one of five levels between 4.8 deg/s and 8.3 deg/s. We did not acquire extensive comparison task results using triangular harmonic gratings as we found that participants did not perceive the reference scales as sufficiently differentially transparent, which is a critical requirement for the use of a reference scale to measure perceived transparency strength with the comparison task.

Each test stimulus was also made up of a pair of independently moving gratings, one of which – referred to as the fixed parameter grating – had a standard set of parameters i.e. a speed of 3.2 deg/s, fundamental spatial frequency of 0.263 cycles per degree and a luminance of 36 cd/m^2. For all stimuli used in these experiments, it is important to note that where the term spatial frequency is used as a stimulus parameter, it refers to the fundamental frequency of the broadband harmonic grating stimuli. The spatial frequencies of the harmonics in the stimulus scale with that of the fundamental. The second grating in the test stimulus was the variable parameter grating in which the fundamental spatial frequency, relative luminance or speed were varied during the experiment. Both the fixed and variable parameter gratings in the case of the square harmonic gratings were constructed from five odd harmonics, the same number of harmonics as the mid point of the five reference scale stimuli. In the case of the periodic line gratings, the test stimuli had a fixed speed difference of 6.4 deg/s, also the centre point of their reference scale. The relative luminance refers to the ratio of the luminance of the variable parameter grating to that of the fixed parameter grating. We used the measure of relative luminance rather than contrast or some other measures as we were interested in the effect on the trend of perceived transparency strength when relative component luminance was changed for the different types of stimuli, rather than quantifying the absolute effects. The relative luminance of the variable parameter grating was set to values of 0.1, 0.2, 0.4, 0.8 and 1.0, relative to the fixed parameter grating which corresponded to luminance values of 6.5, 12.2, 20, 32 and 36 cd/m^2. These luminance values are the result of adjusting the luminance of both components so that the superposition uses the full range of the display and the overall contrast remains the same. For the experiments with the periodic moving lines, the relative starting positions (or initial phase) of the fixed and variable gratings in the test as well as the slow and fast gratings in the reference were randomised in all presented stimuli so that the line crossover points could not be used as a cue to transparency for the briefly presented stimuli. The experiments that followed looked at the effect of speed difference, spatial frequency difference and relative luminance between the variable and fixed parameter gratings on perceived transparency strength of the test stimulus, measured in terms of the equivalent stimulus of the reference scale.

3.2. Procedures

Participants were requested to ensure they kept their eyes fixated on the centre of the stimulus on a small round spot (0.25° and fixed at 28 cd/m^2) to avoid the effects of eye movements during stimulus presentations. They used a chin and forehead rest for the tasks. A trial contained a test and stimulus interval in randomised order, each on for 750 ms with a 500 ms inter-stimulus interval in which a grey screen (36 cd/m^2) containing a fixation was presented. The time was chosen to ensure that local signals were fully integrated into a global signal before the perceptual decision was made. After each trial the participant was asked to make a forced-choice decision about which of the two-intervals appeared more strongly transparent. The decision was recorded by clicking with the mouse on one of two boxes displayed on the screen (labelled "First" and "Second") after the test and reference stimuli were presented. The direction of movement of the gratings in the stimuli was reversed after each presentation interval of the moving stimuli to reduce directional adaptation effects. The proportion of test stimuli perceived as more transparent than the reference stimuli was calculated for each of the reference scale points measured, and a psychometric curve fitted using a logistic function implemented in Matlab. The point of subjective equality (PSE) was used to quantify the transparency strength for the given test stimulus at the 50% point of the logistic fit in units of the reference stimulus parameter (see Fig. 3d). Each PSE was typically measured four times, and the average and standard error of the mean were plotted. For each tested variable, five reference stimuli and five test stimuli were used so that a total of 250 trials were repeated four times for complete participation in a given condition. In these experiments, we randomised the assignment of participants to task blocks and used each person for only part of the experiments to try to keep the time requested from each volunteer participant to a minimum.

3.3. Results: harmonic square gratings

A systematic dependence of the strength of perceived transparency of square wave gratings on the speed difference was found, shown in Fig. 3a. for a range of speeds of 0.64–5.12 deg/s. Stimuli with low speed difference were found to be less transparent for all participants, measured at about 3.5 harmonics at a speed difference of 0.64 deg/s. Transparency strength increased to five harmonics at the speed difference of 1.92 deg/s from where the increase in the measured transparency strength with speed difference was no longer as pronounced for higher speed differences for any of the participants. The speed difference of 1.92 deg/s is marked with a dotted line in Fig. 3a and represents the stimulus parameters for which the test stimulus and the reference stimulus, which forms the centre of the harmonic scale, with five harmonics, are identical. This is a point of physical equality in the data and the speed difference of 1.92 deg/s should therefore have a perceived transparency strength of five harmonics. This point is indicated by the intersection of vertical and horizontal dotted lines in Figs. 3, 4 and 7. The data shows a trend which appears to be approaching a saturation of perceived transparency with speed differences above 1.92 deg/s. The error bars show the standard error of the means. The data shows that despite some variability between individuals, the overall trend is reliably reproduced.

The dependence of perceived transparency strength on the relative luminance of the variable parameter grating is shown in Fig. 3b. The perceived transparency strength remains approximately the same for the range of relative luminance investigated, measured as five harmonics, except at the lowest relative luminance level of 0.1, where for three out of the four participants a substantial reduction in transparency strength is measured. At this lower relative luminance, the variable parameter grating could be approaching the limits of detection due to its low contrast. Participants indeed reported the variable grating component as being "difficult to see". The data suggest that as long as both gratings are clearly visible, transparency perception may not benefit from the two components being more clearly discriminable in terms of grating luminance or contrast. Participant JB shows a strong increase in transparency strength for the mid range relative luminance of 0.4 (see Fig. 3b). This result suggests that for this individual, the difference in luminance between the standard and variable parameter gratings serves as a cue that aids the separation of the components.

The strength of perceived transparency was also found to be dependent on the difference in fundamental spatial frequency between the variable parameter grating and the fixed parameter grating of the test stimulus, as shown in Fig. 3c for the range of differences in fundamental spatial frequency of −0.053, −0.026, 0, 0.053 and 0.105 cycles/deg. These were obtained by keeping the fixed parameter grating at a constant spatial frequency of 0.263 cycles/deg and setting the variable grating parameter at fundamental spatial frequencies of 0.210, 0.237, 0.263, 0.289, 0.316 cycles/deg. A strong trend was observed for all participants with negative spatial frequency differences (lower frequency variable grating compared to fixed grating) being perceived as less transparent than positive spatial frequency differences (higher frequency variable grating compared to fixed grating), with an intermediate transparency strength of five harmonics at the point of physical equality.

3.4. Results: periodic line gratings

The transparency percept for periodic lines is measured against a speed difference reference scale in this section. Both the relative luminance and the spatial frequency are varied in the variable grating of the test stimulus during the investigation. The dependence of perceived transparency strength on relative luminance is shown in Fig. 4a, measured for the range of ratios 0.2, 0.4, 0.6, 0.8 and 1. The perceived transparency strength was observed to be consistently reduced by reductions in the relative luminance for all participants throughout the range tested. This could be attributable to the reduced visibility of the thin darker lower luminance lines. The periodic lines presented were one pixel wide (compared to a ~35 pixels wide light region in a typical square harmonic grating) so that the local motion responses they elicit in the visual system would be more strongly affected by small reductions in luminance than those of the harmonic luminance gratings.

The difference in fundamental spatial frequency of the fixed and the variable parameter grating was tested with the same range of values used with the square harmonic gratings in Section 3.3. A weak trend in the strength of percept was observed in which negative spatial frequency differences reduced transparency strength, while positive differences increased perceived transparency strength, as shown in Fig. 4b. This trend to some extent replicates that found for harmonic luminance gratings in Fig. 3a, though not as consistently between participants and with larger variability within observers. These results obtained using the periodic lines demonstrated that the comparison task generalises such that any reasonable reference scale can be used to measure transparency strength. The effect of fundamental spatial frequency difference on perceived transparency strength suggests a common mechanism behind the percept both for line and square harmonic stimuli.

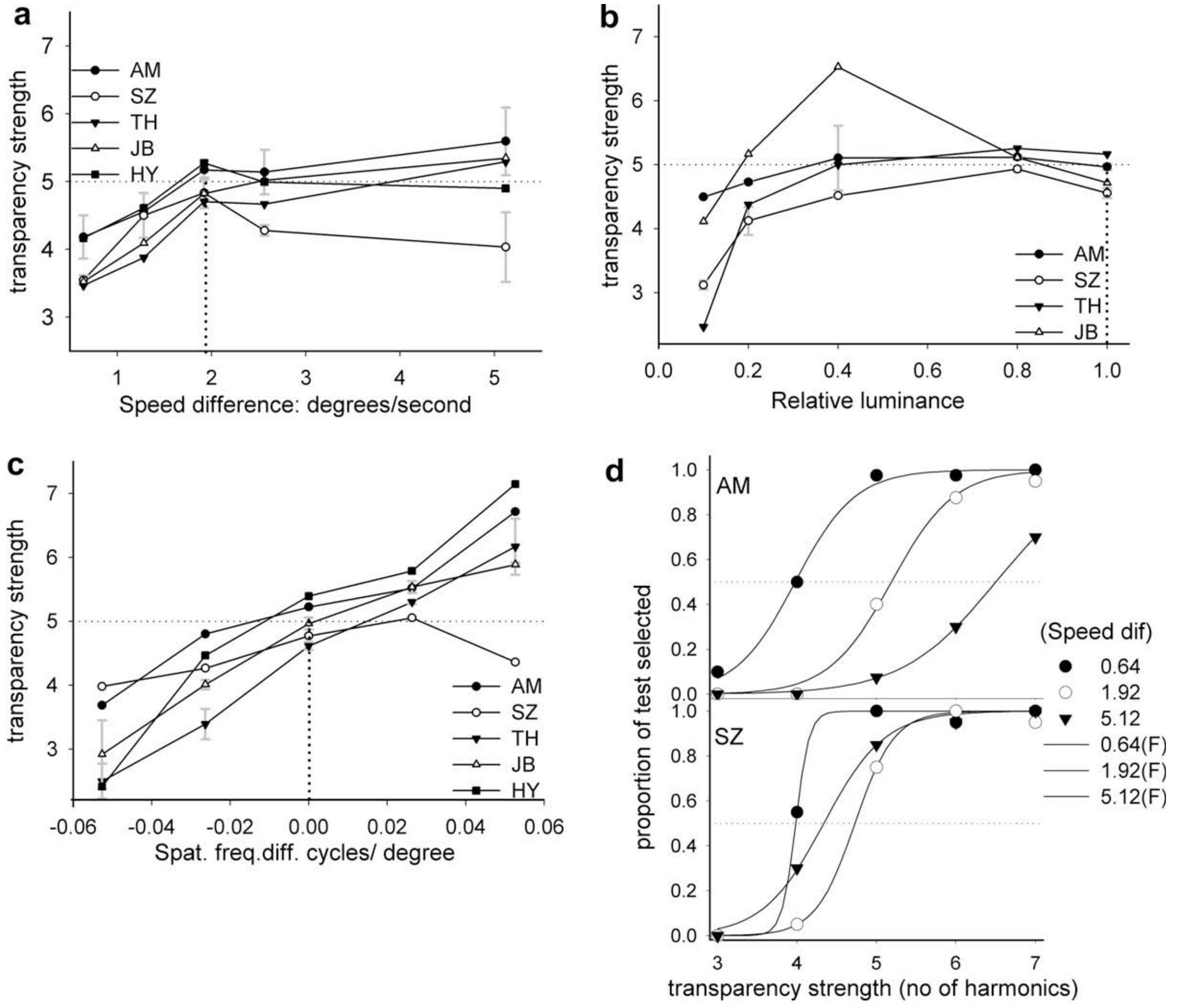

Fig. 3. The effect of stimulus parameters on perceived transparency strength for square harmonic gratings. Transparency strength is measured using a two-interval comparison task in units of the perceptually equivalent number of odd harmonics on the reference scale stimulus. Three different test grating parameters are investigated by varying parameter values of the variable parameter grating (see text). (a) Speed differences between components: small speed difference less transparent until what may be a saturation from about 1.92 deg/s. (b) Relative luminance: little effect seen for four participants, perceived transparency remains the same except at the lowest measured relative luminance of 0.1. (c) Spatial frequency difference: a negative spatial frequency difference appears less transparent than positive spatial frequency difference. (d) Actual psychometric curves for two participants, SZ and AM from the results in (a) showing the proportion more transparent for the extreme ends of the data points and the mid points together with the logistic curve fits.

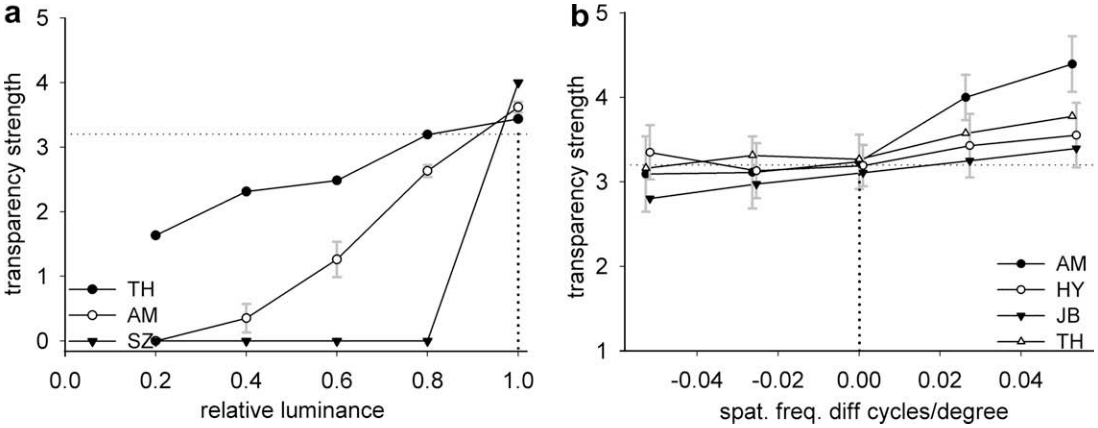

Fig. 4. The effect of stimulus parameters on perceived transparency strength of moving periodic lines. Percept strength is measured in units of speed difference between the slower and the faster reference scale gratings, in deg/s, using the comparison task described in the text. The investigated stimulus parameters are varied for the variable parameter grating of the test stimulus. (a) Relative luminance: lowering the relative luminance of one component makes the stimulus appear less transparent for all participants. (b) Spatial frequency difference: in general, negative spatial frequency difference (lowering frequency) appears more transparent than positive spatial frequency (higher frequency) but the effect is stronger for some participants.

4. Experiment 3: static transparent stimuli

4.1. Stimuli

The moving square wave grating stimuli may have contained both motion and form cues which aided perceptual separation of components. By form cues, we are generally referring to any visual cues which may aid perceptual separation of transparent scenes in the absence of motion. It therefore follows that some visual cues may well be simultaneously detected by both motion and form mechanisms within the visual system. We carried out the experiments in this section under the assumption that all relevant available cues within a given visual stimulus are used to arrive at a perceptual decision, in the case of our tasks, a perceptual separation of components. We therefore tried to measure the effect of manipulating any such form cues contained within static stimuli by varying similar low level stimulus parameters used in the moving grating experiments. In this control experiment, we used a static transparent stimulus constructed from two superimposed grating like components. To construct the static transparent stimuli, we used the Mettelli conditions of transparency (Metelli, 1974) to create a rectangular object which is perceived to lie transparently above its background, as shown in Fig. 5. To make our static stimuli comparable to our moving stimuli, we set up a low frequency (one cycle in the image) square wave grating as the background. This background is analogous to the fixed parameter grating in the moving test gratings or in the case of the reference grating, the slower moving grating. On top of this background a grating a quarter of a cycle out of phase from the background is non-linearly superimposed. This foreground rectangle is analogous to the variable parameter grating of the moving test stimulus or the slower grating in the reference stimulus. The vertical dimension of the superimposed grating is smaller than the background to create the luminance junctions at the upper and lower border of the object also necessary for perceived static transparency. Though this vertical gap makes the stimulus fundamentally different from the moving one dimensional gratings, as part of the figural cue, it is as critical for their transparency as motion is for transparency with the gratings (Beck & Ivry, 1988). We did not seek to create identical static and moving stimuli and therefore did not see these differences in stimulus appearance as being critical. Our goal was primarily to create a transparent static stimulus in which the effect of varying comparable low level stimulus parameters could be measured.

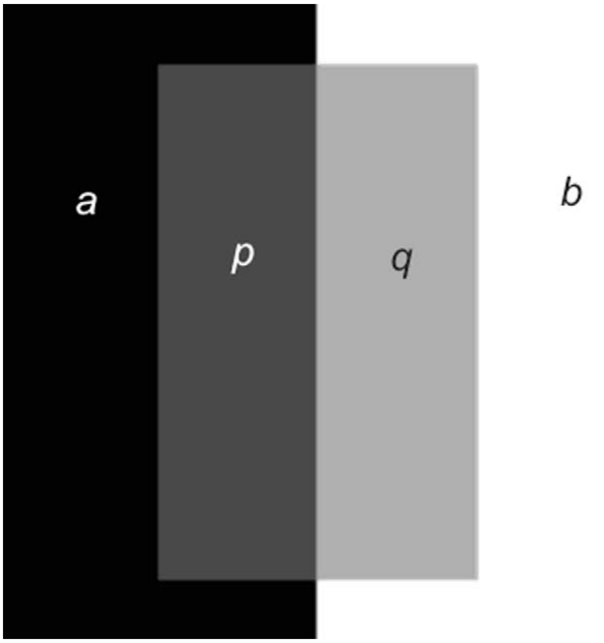

Fig. 5. An image of the static transparent stimuli. There are four luminance levels given by the letters *a*, *b*, *p* and *q*. The background which is also the fixed parameter grating is defined by the black and white luminance at *a* and *b*, respectively. The transparent grey object which is the variable parameter grating is given by the levels *p* and *q* whose luminance values are calculated to meet the Metelli polarity and magnitude constraints for perceiving luminance transparency. The central region should appear as a transparent layer on a depth plane above the black and white background.

To make a static object appear transparent, the superposition needs to satisfy Eqs. (5), (6). The labels *a*, *b*, *p* and *q* indicating the luminance values in the four regions in Fig. 5 correspond to the variables used in Eqs. (5) and (6).

$$p = \alpha \cdot a + (1 - \alpha) \cdot t \quad (5)$$

$$q = \alpha \cdot b + (1 - \alpha) \cdot t \quad (6)$$

These simultaneous equations can be solved to establish a magnitude and polarity constraint based on the physical characteristics of the stimulus. From these, the polarity and magnitude constraints were established by Metelli. (1) Polarity constraint: $p-q$ must have the same sign as $a-b$, leading to $\alpha \geqslant 0$. (2) Magnitude constraint: $|p-q| < |a-b|$.

In Metelli's original equations α and t were the transmitted light (i.e. the fraction of light passing through the foreground) and the light actually reflected by a rotating episcotister stimulus. For our stimuli which emit light from the display screen, α therefore has no physical relevance in the same way but still quantifies the fraction of the background luminance (a or b) which can be seen through the transparent surface, and like t, varies in value from 0 to 1. When generating our stimulus, we used Metelli's formulae to vary these parameters as done in previous work with transparent stimuli presented on monitors (Beck et al., 1984; Singh & Anderson, 2002). The transparent object defined by areas p and q shown in Fig. 5 can have its luminance and spatial frequency parameters set independently. We used as the luminance the value of t, which modulates the luminance of a component grating displayed on a computer monitor. The fundamental spatial frequency was varied like that of the moving grating stimuli, increasing the horizontal width of the foreground rectangle for lower spatial frequency and decreasing the width, introducing additional cycles of the grating sitting on either side of the centre for higher frequencies (see insets in Fig. 7 for graphic illustration of different static stimuli).

4.2. Procedures

The static transparent stimuli were tested psychophysically using both the subjective procedure described in Section 2.1 and the comparison task described in Section 3.1 for moving stimuli. When participants were asked to subjectively evaluate the strength of transparency in static patterns, it was described to them as the vividness of the percept of a rectangular plane lying in front of the black and white background. The richness of the Fourier spectra of the stimuli was varied by applying a two dimensional low pass Gaussian filtering so that the constant σ in pixels was a single continuous parameter. Harmonic gratings were not used here because of the complexity of the static transparent stimuli which unlike the moving gratings have a two dimensional structure. The comparison task was carried out using five stimuli with a range of values of σ as the reference scale, while fundamental spatial frequency, luminance, and geometrical configuration were varied.

4.3. Results: subjective experiments

In presentations of the static transparent stimulus to participants in a subjective psychophysical task, the size of the Gaussian low pass filter constant σ was varied from 0.5 pixels to 3.5 pixels (0.025–0.173°). Such lowpass filtering increasingly removes the higher spatial frequency components from the stimulus, and makes it appear less transparent. The results of these subjective estimates, which are very consistent between all five participants, are shown in Fig. 6. The filter constant σ, like the number of harmonics in the grating stimuli, determines the richness of the Fourier spectrum. This result therefore corresponds to those described in Section 2.3, showing that stimuli with rich Fourier spectra appear more strongly transparent. The reference stimulus set is therefore constructed using the lowpass filter width as the variable to create five different levels of perceived transparency, measured in units of σ.

4.4. Results: comparison task

The comparison task was used to assess quantitatively the effect of varying spatial frequency and luminance on the perceived transparency strength in static patterns. We first carried out the comparison task for test stimuli in which we measured the dependence of perceived transparency strength on luminance using the parameter t from Metelli's equations (Eqs. (5) and (6)). The results of the relationship between perceived transparency strength and t are shown in Fig. 7a. All participants show a direct dependence of perceived transparency strength on the luminance so that when luminance is lowest (0.2) the stimuli appear most strongly transparent; the perceived transparency strength weakens as the luminance increases. This trend is in the opposite direction to that observed for the transparently moving grating stimuli in Figs. 3b and 4a. There are individual differences in the curves, but for all participants, a reduction in t increases the perceived transparency strength of the stimulus.

The dependence of perceived transparency strength on spatial frequency difference is shown in Fig. 7b. The fundamental spatial frequency of the variable parameter grating was tested for a range of 0.053, 0.079, 0.105, 0.158 and 0.211 cycles/deg with the fixed parameter grating kept at 0.105 cycles/deg. The perceived transparency strength appears to be dependent on the difference in fundamental spatial frequency so that at the lowest spatial frequency difference used (−0.053 cycles/deg), the presented static stimulus was perceived as least transparent while at the highest (+0.105 cycles/deg), it was most transparent. The data shows quite a bit of variation but the trend can be seen to be similar to that of the transparently moving gratings shown in Figs. 3c and 4b. This dependence on spatial frequency may however be argued to be an effect based entirely on object size which varies with the spatial frequency. To control for such an effect, we tested the dependence of perceived transparency on the vertical size as a fraction of the fixed parameter grating using the range of 0.6, 0.7, 0.8, 0.9 and 0.98 for the variable parameter grating. We found that there appeared to be no systematic relationship between vertical size and perceived transparency strength except at the largest vertical size of grating (see Fig. 7c), for which the visibility of the junction of the foreground variable parameter grating with the background black and the white is reduced. This junction is a necessary part of the figural cues for transparency and the size therefore only affects the percept at this largest end.

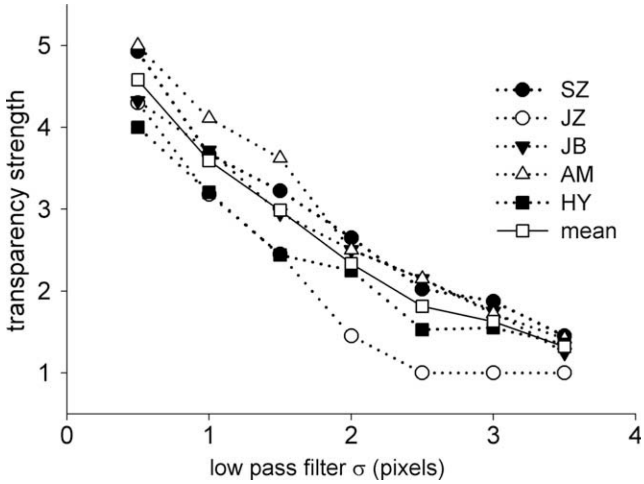

Fig. 6. Subjective transparency strength ratings for static transparent stimuli. The responses for five participants in the dotted lines and the average of their responses is shown in the solid line. As the size of the Gaussian low pass filter used is increased in the range from 0.5 to 3.5 pixels, reported transparency is seen to get weaker.

5. Discussion

We investigated the perceived transparency of two gratings moving in the same direction at different speeds using square harmonic gratings and periodic line gratings. We initially explored the moving stimulus with subjective experiments which revealed differentially transparent perception when certain stimulus parameters were varied. To carry out more reliable psychophysical experiments, we developed a two-interval forced-choice comparison task which enabled us to quantify the strength of perceived transparency for a range of stimuli. We described how the psychophysical task could be generalised for use with any transparent stimulus. We then identified important properties of the gratings that determine the strength of perceived transparency by manipulating grating waveforms and parameters which affect the ability of human observers to discriminate the two transparent components, such as speed difference, the difference in fundamental spatial frequency and relative grating luminance.

For speed differences, we found that for very small differences, the grating pairs appeared weakly transparent, and that with increasing speed difference stimuli were perceived as more strongly transparent. Transparency strength appeared to begin to level off, increasing only slightly with increasing speed difference at the larger speed differences tested (see Fig. 3a). This increase in perceived transparency strength and its apparent approach to a maximum level is interpreted by us as consistent with a signal detection task, which separates motion signals corresponding to the separate stimulus components from a combined signal distribution, as previously proposed for transparently moving stimuli with directional differences (Clifford & Vaina, 1999; Edwards & Nishida, 1999). Taking such a description in the speed domain, the speed difference will determine the separability of the components such that the distance between the two distribution modes, together with their spread, determines transparency strength. The observation of a continuous increase in transparency strength is consistent with a single speed tuned system for motion perception with an upper and lower speed sensitivity limit (Van Boxtel et al., 2006). Within the speed difference range tested, it appeared the components were not entirely independently detected and as a result may interfere with each others cortical representations. Separation cannot further improve when the two signal distributions no longer overlap at a given noise level. Once such a separate, independent representation of components is reached, further increase of the speed difference may go on to shift the faster component outside of the favourable operating range of motion detectors, thus

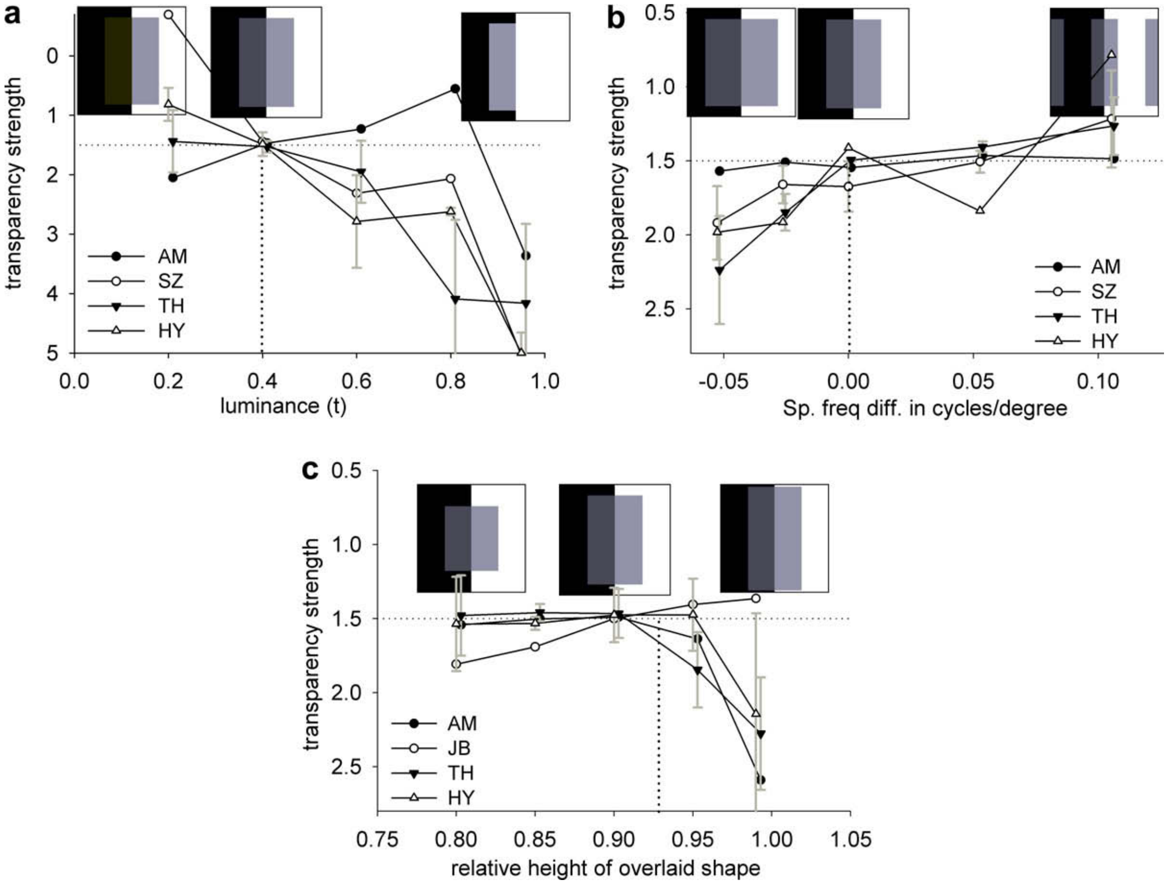

Fig. 7. Perceived transparency strength of static stimuli measured in units of low pass filtering constant σ in pixels using the comparison task. The reference scale is a set of static transparent images blurred with five different sizes of filter σ and compared to test stimuli in which the variable parameter foreground has its luminance and fundamental spatial frequency settings varied in the investigation. The diagrams inset show images of the appearance of different parameter settings of the stimuli. (a) Relative luminance given by t from Metelli equations (see text) is found to have an inverse relationship to transparency strength: lower luminance is perceived as more transparent than higher luminance. (b) Spatial frequency difference between foreground and background is monotonically related to transparency strength, negative differences are less transparent than positive difference. (c) As a control for the spatial frequency effect, the vertical size of the stimuli shows an effect which is not as pronounced and consistent as the spatial frequency effect.

affecting sensitivity to this component, and making the components less separable, as illustrated in Fig. 8c.

For both moving grating types tested with the comparison task, we found a consistent dependence on the difference in fundamental spatial frequency (see Figs. 3b and 4a), suggesting the use of a common neural mechanism behind processing the two grating types which is modulated by the fundamental spatial frequency of components. Observers showed smaller perceived transparency for lower spatial frequency of the variable parameter grating, as compared to the fixed grating, and a stronger percept for higher spatial frequencies. The trend appears to be a monotonic increase in the case of the square harmonic luminance gratings, but less well defined in the periodic line gratings. We observed considerable individual differences, particularly when participants were presented with the periodic line gratings. These individual differences may be the result of inherently noisy measurement scales or a difference in the way participants used available cues within the stimuli. The fundamental spatial frequency of moving square harmonic or line gratings is directly related to the density of local motion signals in the image. The higher the fundamental spatial frequency of a square harmonic grating, the higher the density of edges, and therefore also that of local motion signals at these edges. The direct relationship between the fundamental spatial frequency and density of edges considered along side the consistent results when varying spatial frequency serve as more evidence that the richness of Fourier spectra, and not higher frequencies themselves, aids transparency perception. We expect that a higher density of local motion signals may serve to increase the amplitude of the integrated global motion signal attributable to the higher fundamental frequency grating component, and hence can explain the stimulus becoming more strongly transparent as this component becomes easier to detect. This is illustrated in Fig. 8d, where component V_2 has a stronger and less noisy global motion signal than V_1. Such an interpretation invoking local motion signal density would also explain the asymmetry about the point of physical equality in the stimulus. Symmetry about this zero difference point would be expected if different spatial frequency tuned channels processed the different components, as suggested for plaid patterns (Adelson & Movshon, 1982; Stone et al., 1990) and illustrated in Fig. 8a. The increase in perceived transparency strength with increasing density of local signals at the edges can only be sustained while local signals are sufficiently sparse that they do not have a high chance of locally interfering with each other. When local signals start interfering with each other, the local motion detection process is disrupted and the percept would be quickly disrupted and eventually lost (Braddick et al., 2002; Qian et al., 1994). This would correspond to a reduction in amplitude of components V_1 and V_2 in Fig. 8b and d. There is therefore a limit to the extent to which increasing local signal density could aid transparency perception.

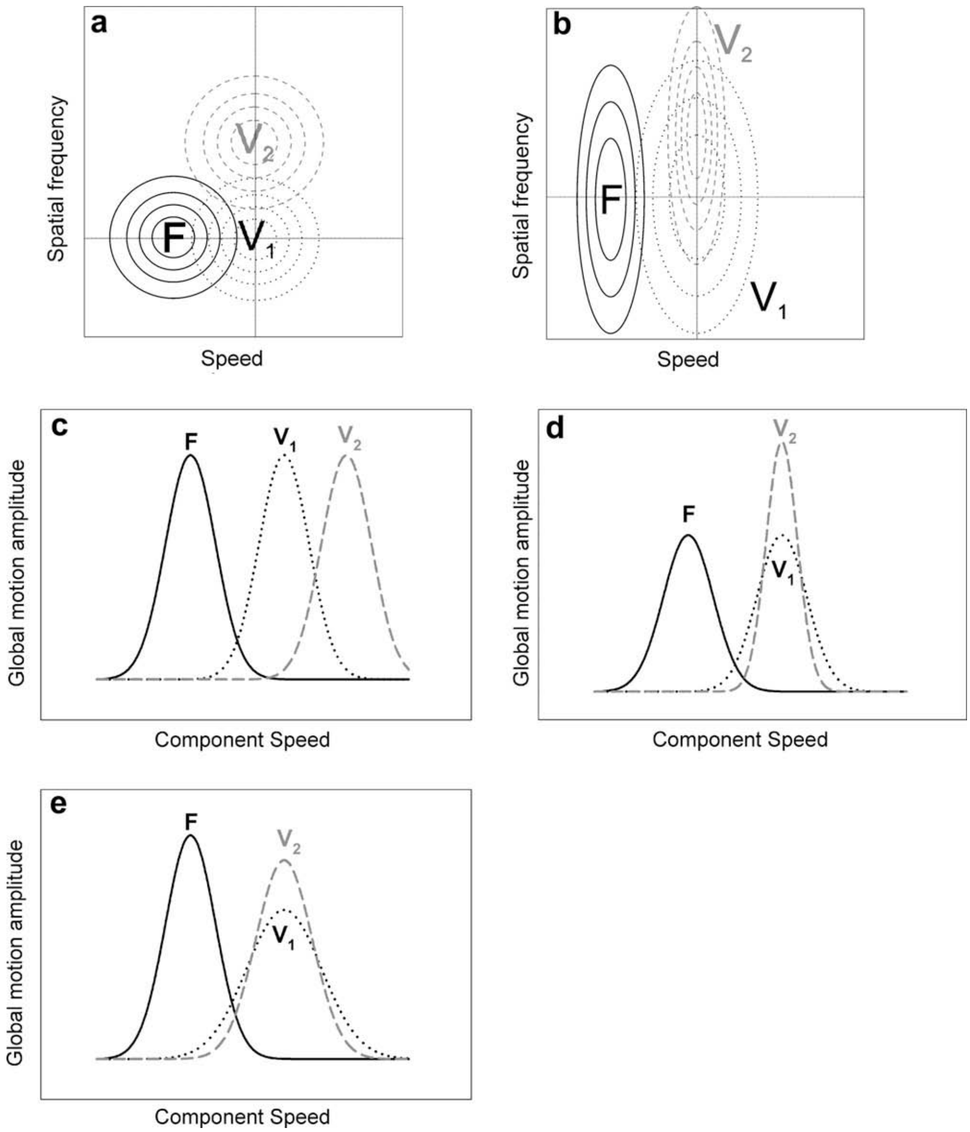

Fig. 8. An illustration of how the expected perceived transparency strength for a range of stimulus configurations depends on the separation of signal distributions in a signal detection task. Stimuli containing a fixed parameter grating *F* and one of two variable parameter gratings V_1 or V_2 are considered. The distributions of local motion signals from each transparent stimulus component are considered in two dimensions (stimulus speed and spatial frequency, where histogram amplitudes are represented by contour lines) for (a) and (b), and in one dimension, speed, for broadband stimuli in (c), (d) and (e), where the histogram amplitude is represented along the *y*-axis. The stimuli are more transparent when the component peaks can be seen as clearly separate. (a) A narrowband transparent stimulus appears as concentric circles in the two dimensional representation. Changing the spatial frequency of components from V_1 to V_2 makes the stimulus appear more transparent with the same speed difference by separating the stimulus along the spatial frequency axis. (b) A broadband square harmonic grating stimulus would have components elongated in the spatial frequency axis and is therefore not separable in the same way as narrowband stimuli in the two dimensional space. Changing the fundamental spatial frequency in this stimulus changes the amplitude and noise properties of the global signal histogram so that a higher frequency component V_2 is more separable from *F* than V_1. The elongated broadband stimuli are therefore better represented by a signal separation in the speed domain. (c) Separation of the slow fixed grating *F* from a slightly faster component V_1 compared to a much faster component V_2. V_2 is shifted further rightwards from *F* than V_1. (d) Separation of the fixed grating *F* from a lower fundamental frequency component V_1 and then compared to a higher frequency component V_2 with the same speed difference. V_1 has a lower histogram amplitude than *F* or V_2, which increases for a higher frequency fundamental as the number of local motion signals is larger. (e) Separation of the fixed grating *F* from a low luminance component V_1 with a lower amplitude global motion response compared to a higher luminance component V_2 with the same speed difference. V_1 has a lower amplitude global component signal than both *F* or V_2. These are for illustration only as the interaction between the transparent components is not a simple linear interaction.

The dependence of perceived transparency strength on relative pattern luminance showed different trends for the two moving grating types. While the periodic lines showed weak transparency with low line luminance and strongest transparency with a line luminance ratio of 1.0 (see Fig. 4a), the harmonic square gratings showed little or no reduction in perceived transparency strength as the relative luminance of the variable parameter grating was reduced, until the luminance of one component is dramatically reduced (when relative luminance was 0.l, see Fig. 3b). This difference in perception of the two broadband transparently moving stimuli – periodic lines and the square harmonic gratings – could have been the result of additional cues within the square harmonic stimuli influencing their perceptual separation. Alternatively, the detection thresholds for the moving periodic lines could also be much higher than those of the harmonic luminance gratings simply because the lines are only one pixel wide and therefore provide less stimulus energy across spatial channels than the harmonic luminance gratings (typically ∼35 pixels wide light/white bar in gratings). It is not easy to conclusively differentiate between either of these alternative explanations or even some combination of both explanations given our data. The reductions in relative luminance for the harmonic gratings used during the experiment appeared to be well above the detectable threshold for most of the range of luminance (according to subjective reports) and therefore had little influence on the perceived transparency strength. The higher energy of the harmonic luminance grating stimuli compared to the periodic line gratings means that they are more likely to stimulate a larger number of neurons processing the various image cues than the periodic lines are. The differences in trends seen may be attributed to this effect of higher visibility than periodic lines but at the same time the higher visibility of the luminance gratings may provide additional cues which do not explicitly feed the motion detection system. When the luminance of the variable parameter harmonic grating was reduced, the tendency for an observer to perceive the grating as a separate object from the fixed parameter grating because of its different luminance may have increased. We investigated the possible influence of non-motion cues in the task of perceptually separating square harmonic grating components by looking at the influence of the fundamental spatial frequency and luminance parameters on the perceived strength of static transparent stimuli.

The observation that a richer Fourier spectrum of the gratings and that a higher density of edges appears to modulate the strength of perceived transparency raises questions about the relative contribution of various stimulus parameters to the process of computing the percept. Stimulus parameters such as speed are a pure motion feature, whereas spatial frequency and luminance provide cues that feed perceptual mechanisms that influence discriminability of the components even in the absence of motion. While the effect of speed difference on perceived transparency strength can be explained by considering the motion signals in a signal detection task, the effects observed for spatial frequency and relative luminance are less simple to explain purely in terms of the motion perception system. We sought to further understand what effects any non-motion cues would have when varying the spatial frequency and luminance parameters with static transparent stimuli. We questioned whether for example, the rich Fourier spectrum and specific phase relationship between harmonics would again be useful for perceptual separation in the absence of motion. This was investigated in experiment 3. Although the static stimuli were not simply static versions of the moving grating stimuli, they were designed such that they contained luminance and figural cues that can be used for perceptual separation. Though we could not create an equivalent of the vertical gap between the foreground and background static components in our moving gratings without allowing for luminance changes in the vertical direction (i.e. restricting ourselves to 1D gratings), we suspect that this difference was not critical for what we were trying to show, particularly after the results of the size control we carried out. It was important that we were able to manipulate comparable low level cues within the static and moving stimuli.

The results of our experiments with moving gratings gave strong evidence that the configuration of two patterns moving in the same direction can be perceived as transparent. The low level stimulus parameters were seen to modulate the strength of the percept in a way consistent with a signal detection task separating overlapping speed distributions. The expectation of trends of perceived transparency strength is qualitatively illustrated in Fig. 8a for a narrowband stimulus and then in Fig. 8b for a broadband square harmonic stimuli. The narrowband stimulus shows circularly symmetric distributions corresponding to each component. This suggests that separation of narrowband stimuli could be done along the spatial frequency as well as the speed axis. The broadband stimuli on the other hand are elongated along the spatial frequency axis and therefore necessarily overlap when there is little or no speed difference between components. Any stimulus parameter which influences the global component distributions would influence perceived transparency strength. Non-motion cues could reduce the width of the global distributions by aiding in the selection of local motion signals strongly corresponding to the components and minimising noise. The signal processing mechanisms sketched in this illustration are investigated in detail in our companion work, treating theoretical and computational aspects – at the present stage Fig. 8 only serves as schematic representation of the transparency problem and to visualise why we believe the experimental result to be consistent with a signal detection task.

For the static stimuli, the strong and consistent effect of increased perceived transparency strength with richer Fourier spectrum was observed, demonstrated by blurring the images with a low pass filter of different sizes while presenting them to observers in a subjective task. The presence of better defined edges is therefore useful in the component separation necessary for perceiving transparency even with static stimuli. Such a scale based on the richness of Fourier spectra is used as a reference scale in the comparison task with the static stimuli. The dependence of transparency strength on fundamental spatial frequency in the static transparent stimuli was found to be consistent with that of the moving grating stimuli. The trend was somewhat less well defined, showing considerable individual differences in the static stimuli. The larger variability in the experimental data from the periodic line and static stimuli may be due to the inherent noise of the reference scales used for the moving periodic lines and static transparent stimuli. Using speed difference as a reference scale for the periodic lines introduces difficulties as perceived speed does not form a linear scale (Thompson, 1982; Thompson, 1984). A comparable harmonic scale was however not practical for periodic lines which could not be successfully generated by harmonics. In the case of the static images, applying a low pass filter to a multiplicatively superimposed set of images manipulates the richness of the Fourier spectra in a way which may also cause perceptual variance. Under the static transparency configuration, the dependence of perceived transparency strength on the fundamental spatial frequency can no longer be explained with an increase in the density of motion signals at the edges but we assume that the stronger percept still reflects an increase in component signal strength. This effect is likely to be related to that observed with the moving stimuli and may be a result of low level filtering mechanisms which also process the input image before motion perception, thus sharing noise properties which depend on the density of the edges of the input. This is further evidence that stimuli with richer Fourier spectra provide stronger local signals aiding component separation.

When varying luminance, the periodic lines showed weakest perceived transparency with low line luminance and the square harmonic gratings showed little or no reduction in perceived transparency strength as the luminance of the variable parameter grating was reduced for most of the range. In contrast, the static transparent stimuli appeared most strongly transparent at the lowest luminance. A reduction in component luminance had differential perceptual effects on the three stimulus types. If there is a dependence of the percept strength on form cues (in this case different luminance levels which distinguishes components), it may be the case that present form cues are brought into conflict with motion cues in different ways within the three stimuli. In the case of the harmonic grating stimuli, motion cues to transparency would be weakened as a result of the weaker local motion signals from a lower contrast component. At the same time the form cue resulting from the lower contrast would make one component appear more perceptually different from the other. The combined effect of this conflict may explain why perceived transparency strength remains largely unaffected by the relative luminance

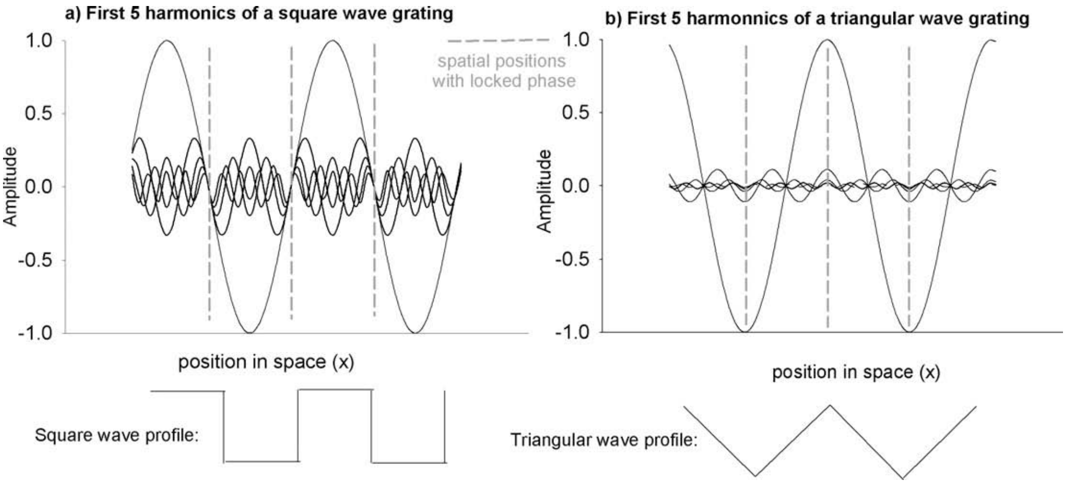

Fig. A1. The first five harmonics of a square and a triangular wave grating. The amplitude of each of the harmonics shown is given by Eqs. (3.2) and (3.3). The vertical dashed lines show the spatial positions along the grating at which the harmonics are in phase. (a) For the square wave, the harmonics are in phase only when the fundamental has an amplitude of zero, which forms the edges of the square wave. (b) For the triangular wave, the harmonics are in phase both at the maximum and at the minimum amplitude points of the fundamental.

(see Fig. 3b). The measured dependence of the percept strength on the luminance for the static stimuli shown in Fig. 7a appears to be consistent with this idea; when the motion cues are removed, then the form cue dominates, making separation easier. In the case of the moving periodic lines, they show a result consistent with a predominantly motion based cue contribution. In the case of the harmonic gratings, it appears that under the tested stimulus conditions, the direct discriminability of the two motion components (in terms of their appearance based on luminance) has a minor contribution to the perception.

6. Conclusions

The work presented here extensively tested the same direction configuration of perceived motion transparency which has previously been reported for white noise patterns (Van Doorn & Koenderink, 1982) and RDKs (Masson et al., 1999). Using this condition, we explored a novel transparently moving one dimensional grating stimulus and demonstrated that the Fourier amplitude and phase spectrum of transparent stimuli plays a role in the perceptual separation of components for both moving and static stimuli. We showed that the described comparison task was a reliable method for quantifying perceived transparency strength for a range of stimuli, for several psychophysical observers. In the case of the moving stimuli, where speed differences are critical, it can be suggested from our results that the presence of stronger edges aids in the task of separating components using a speed tuned motion perception system capable of simultaneously representing at least two transparent components. There may therefore be a more general role for the amplitude and phase spectra, particularly the role of edges, where the determination of speeds or the processing of complex static scenes is involved. Some previous theoretical work has argued for energy extraction in the detection of local motion (Adelson & Bergen, 1985; Adelson & Bergen, 1986), in a phase invariant approach which reduces the importance of phase dependent features such as edges. There are also studies which argue for the importance of phase sensitivity in such energy based detectors (Morrone & Burr, 1988) or even more specifically for a role for discontinuities in contributing to perceptual decisions (Del Viva & Morrone, 1998; Jasinschi, Rosenfeld, & Sumi, 1992; Meso & Zanker, 2009). Results from primate physiological experiments using moving stimuli with and without edges suggest that speed encoding is aided by the presence of edges (Perrone & Thiele, 2001; Perrone & Thiele, 2002). There have also been some suggestions from functional magnetic resonance imaging that regions like MT in human visual cortex have BOLD activity which is dependent on speeds of presented stimuli within the range of speeds we tested, 4–8 deg/s (Chalwa et al., 1999), although the stimulus in this case was expanding optic flow RDK patterns, which are more complex than simple translations. If edges, or any sudden luminance discontinuities in the case of two dimensional stimuli (as present in RDK), enhance speed tuning in motion sensitive neurons which encode global motion, then populations in MT could well simultaneously represent transparently presented components with different speeds, with the aid of *V*1, by maintaining a retinotopic representation of components at the locations of the various edges detected by *V*1. The local and global stages of transparency perception may both simultaneously actively represent the percept, so that accurate positional information is maintained locally while any necessary integration is being carried out globally. Our work, however, did not answer all of the large number of questions posed by transparency perception without directional differences, but rather opens up a number of areas of future study. Transparently moving stimuli need to be explored further to elucidate the role of speed perception, to characterise the relationship between motion and non-motion cues to perceptual separation and to attempt to better understand the precise nature of the neural representation behind the simultaneous perception of transparently moving components.

Acknowledgments

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Appendix A. Harmonic phase relationships

The sine wave is a narrowband stimulus containing a single frequency component. Triangle and square wave gratings contain an infinite number of frequencies, with the energy carried in each frequency component inversely related to the frequency. In terms of the Fourier amplitude, the triangular and square waves are rather similar. A major difference between them lies in the phase (or the imaginary part of the complex function) of the spectra. Square wave harmonics are phase-locked at the zero crossing of the fundamental frequency, resulting in an odd symmetry about the point of phase-lock. Triangular waves are phase-locked at both the maxima and minima of the fundamental with an even symmetry about this phase-lock point as shown in Fig. A1. Perceptual differences between the triangular and square wave gratings may therefore be largely attributable to this difference in phase locking.

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