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Research report

Anomalous perception of coherence and transparency in moving plaid patterns

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Anomalous perception of coherence and transparency in moving plaid patterns

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Abstract

While the low-level processes mediating the detection of primary visual attributes are well understood, much less is known about the way in which these attributes are assigned to objects in the visual world. For example, when a region of the retinal image contains multiple motion signals at a range of spatial scales, how do we know whether these signals come from a single object or multiple objects? Here, we present data from four neurological patients on a psychophysical task requiring them to report whether the two components of a plaid pattern appear to move coherently or transparently. The spatial frequency of one component of the plaid is held constant while that of the other is manipulated. While some of the patients perceive coherent motion over a much smaller range of spatial frequencies than normal controls, others report coherence over almost the entire range tested. We discuss the implications of these findings for computational theories of motion perception and higher-level visual processing.

Keywords: Motion; Plaid; Transparency; Visual cortex; Psychophysics

1. Introduction

We present data from four neurological patients showing anomalies in the perception of coherent and transparent motion. The perception of motion coherence and transparency involves luminance and non-luminance information from across scales. In our everyday environment, motion cues at different scales often arise from a single object. However, there are many conditions where one object occludes or partially obscures another. In order to segment the visual world into objects, and to ascribe the appropriate motion to each object, our visual systems must combine motion over scales and cues in some instances but not in others. For example, when we see a fish swimming beneath the surface of a pond we are aware not only of the motion of the fish, but also of the rippling of the water, and motions from the same regions of our retinal image of the visual scene must be ascribed to different objects.

In the laboratory, the perception of coherent and transparent motions is commonly studied using plaid patterns [1]. A plaid pattern is formed by the additive superposition of two gratings of different orientations moving in different directions. Since the luminance profile of the grating varies in only one spatial dimension, motion parallel to the grating does not affect the luminance of the retinal image and so cannot be detected, a phenomenon known as the aperture problem. Thus, when a single moving grating is viewed in isolation, motion is perceived orthogonal to the orientation of the grating. When two moving gratings are superimposed to form a plaid, the motions of the component gratings uniquely define the speed and direction of plaid pattern motion, a fact which can be expressed geometrically as the intersection of constraints (IOC) [1]. However, the IOC principle does not account for some important psychophysical data on direction perception in plaid motion. Firstly, the perceived direction of plaid motion can deviate significantly from the IOC direction [3,8]. Secondly, Victor and Conte [30] report the case of a patient, CS, whose direction discrimination for plaid patterns was better than for the component gratings. The performance of CS is inconsistent with the IOC principle which predicts that errors in recovering the direction of

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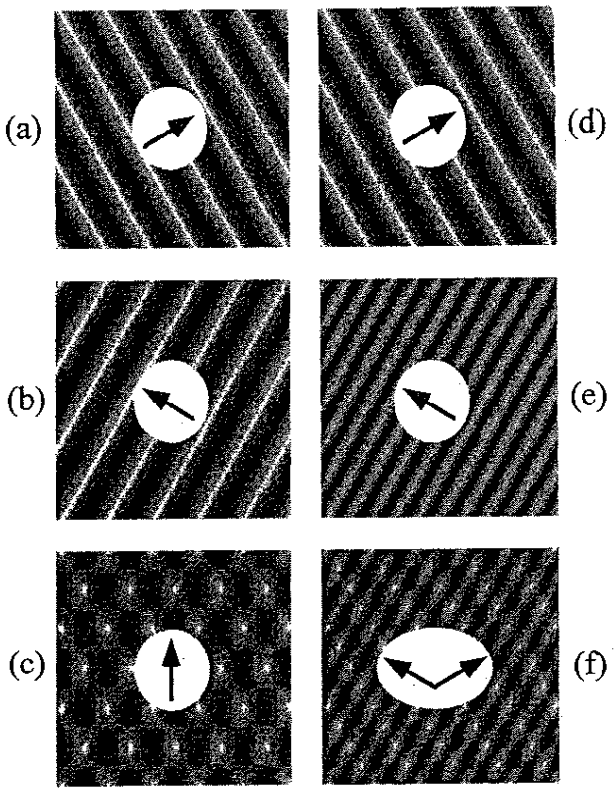

Fig. 1. Two plaid stimuli and their component gratings. (a, b) Drifting sinusoidal gratings of identical spatial frequencies oriented at ±30° to the vertical. Additive superposition of the two gratings produces the plaid pattern in (c), which normal observers perceive as moving coherently in the vertical direction. (d, e) Gratings with spatial frequencies in the ratio 1:2. (f) When component spatial frequencies are sufficiently different, normal observers perceive the two components moving transparently through or over one another, rather than coherent pattern motion.

component motion would be compounded in direction discrimination for a plaid pattern [30].

In many cases the two components of a plaid are perceived to be moving transparently over one another rather than as a single coherent pattern [1,14,26]. One parameter which has been found to influence the perception of coherence in plaid motion is the relative spatial frequency of the two components [1]. Coherence is perceived when the spatial frequencies are identical, but two transparent motions are observed when the spatial frequencies differ by two octaves or more (Fig. 1). Here, we use moving plaid patterns to investigate the mechanisms underlying the perception of coherence and transparency. Four neurological patients and five normal controls were required to report whether a plaid pattern composed of two sinusoidal gratings appeared to be moving coherently or transparently, and their results were recorded as a function of the relative spatial frequency of the two components. The patients were chosen to illustrate the range of interpretations of plaid motion found as a result of neurological deficits. Two of the patients perceived plaids moving in the hemifield contralateral to their lesion as coherent only when the component spatial frequencies were identical, while the others showed biases towards coherence when compared with the normal subjects. To account for the data, we propose a motion processing architecture in which motion is processed by parallel linear and non-linear motion pathways. The model closely resembles that of Wilson et al., with linear and non-linear channels being combined at each spatial scale [31] and feeding into a network in which motion signals from multiple scales interact [14,32].

2. Subjects

The subjects for the experiment were four neurological patients with parietal or occipital lesions and five age-matched normal control subjects. The patients were part of an extensive psychological study of the effects of lesions on visual motion perception. All subjects gave informed consent according to the guidelines of the Boston University Human Subjects Committee (Table 1).

In all patients, visual acuity with correction glasses and eye movements were normal, as were temporal frequency and contrast sensitivity for the detection and discrimination of static or moving sinusoidal gratings with spatial frequencies ranging from 0.2–3.0 cycle/deg presented in either visual field. The patients' performance on tasks of 2-D static form, texture and colour discrimination was also normal. However, all the patients were impaired on a variety of visual motion tasks for stimuli presented in the visual hemifield contralateral to their lesion. Two of the patients were extensively studied and their visual motion perception capabilities reported previously (Patient RA [29]; Patient AMG [28]).

Table 1
Summary of the results of neuroopthalmological assessment and lesion analysis for the four patients

Patient	Sex	Age	Side of lesion	Position of lesion	Visual fields
JK	M	55	Right	temporal; posterior temporo-parietal	normal
AMG	F	52	Left	posterior parietal–occipital (mainly white matter)	right inferior quadrantanopia for small objects
RA	M	66	Right	occipital (involving the cuneus and rostral and medial occipital pole)	homonymous left inferior quadrantanopia (macular sparing)
GT	F	43	Right	occipital (deep white matter ischemia); lateral posterior thalamus	left upper quadrantanopia

3. Methods

Moving plaid patterns generated by additive superposition of two sine wave gratings were viewed through a circular aperture subtending 8° of visual angle. The stimulus was surrounded by a uniform grey field with a luminance equal to the mean luminance of the pattern (22 cd/m^2) and presented for one second. Stimuli were generated on a Macintosh computer and displayed on a Macintosh RGB screen. Two-dimensional spatial patterns were generated by drawing two one-dimensional ramps oriented at 30° on either side of vertical (the IOC direction) into video memory. The appearance of motion was generated by cycling through lookup tables containing sinusoidal values. The two components always had the same contrast of 30%. The spatial frequency of one grating remained fixed at 1 cycle/deg while that of the other was varied between 0.25 and 2.5 cycle/deg in steps of 0.25 cycle/deg. The temporal frequencies of the gratings were chosen to ensure that the speed of each was maintained at 3°/s. Every pattern was repeated 22 times. Observers sat 1 m from the screen in a darkened room, and were instructed to maintain fixation on a spot 6° from the centre of the stimulus aperture. All subjects reported that the entire stimulus was in view under these conditions. The experimental task was to indicate whether the moving pattern appeared "coherent" or "transparent".

4. Results

The results from the four patients and the average of the data from the five normal controls are presented in Fig. 2.

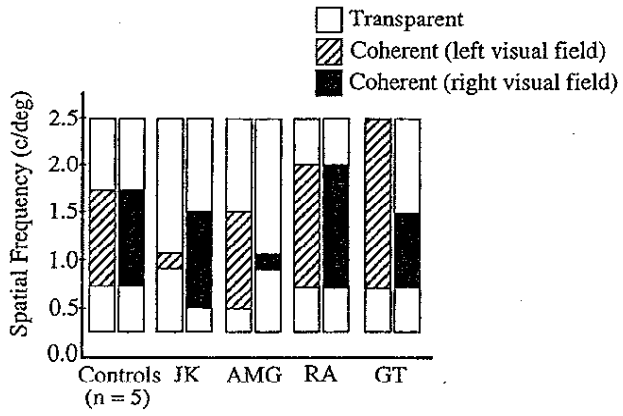

Fig. 2. Plaid coherence/transparency data from the four patients and a group of five normal controls. Subjects report whether the plaid pattern appears to be moving coherently or transparently. The spatial frequency of the first component is fixed at 1.0 cycles per degree, while that of the second is varied. The hatched and shaded areas represent the range of spatial frequencies of the variable component for which motion was judged coherent on at least 75% of trials. Data is shown separately for each subject's left (hatched) and right (shaded) visual field. Details of the site and laterality of each patient's lesion are given in Table 1.

For each visual field of each observer, the shaded regions represent the range of spatial frequencies of the variable component of the plaid for which coherence was perceived at least 75% of the time. For the normal controls, the plaid appeared coherent for the spatial frequency range 0.75–1.75 cycle/deg. For patients JK and AMG, plaids in the hemifield contralateral to their lesion were only perceived as coherent when the component spatial frequencies were identical, while in their ipsilesional field both patients reported coherent motion over the normal range. GT showed a bias towards perceiving plaids presented in the contralesional field as coherent, while RA showed a bias towards coherence bilaterally. Other patients, not described here, showed impairments in motion processing but were not anomalous in their perception of coherence and transparency in plaid patterns.

5. Discussion

When the two sinusoidal components have the same spatial frequency, the motion of a plaid appears coherent to normal observers. When the spatial frequencies are very different, motion transparency is reported. Fig. 3 shows schematically the power spectrum of a plaid pattern in which the spatial frequency of one component is varied. Each sinusoidal grating is represented by a pair of dots placed symmetrically about the origin. Distance from the origin corresponds to spatial frequency; angular position corresponds to orientation. For clarity, only the spatial frequency spectrum is shown. In Fig. 3a, the spatial frequencies of the two components are equal, and they pass through the same spatial filter, the passband of which is denoted schematically by the areas enclosed by the dotted lines. In this case strong signals from the linear and non-linear channels are present at the same scale. In Fig. 3c, the component spatial frequencies are very different and only one passes through the original spatial filter, while the other is processed by a parallel filter (not shown) tuned to a higher spatial frequency. In this case there are signals present at different scales in the linear channel, but no response from the non-linear channel. Fig. 3b represents the case where the difference between the spatial frequencies is such that they excite same filter only to a small degree, giving rise to a weak signal in the non-linear channel.

How do these frequency space representations translate into judgements about motion, and specifically coherence and transparency? The motion of a sinusoidal grating viewed in isolation is only uniquely defined in the direction orthogonal to the orientation of the grating, and is in fact consistent with an infinite number of velocities lying on a line in velocity space (Fig. 4). When only one sinusoidal grating is present, it is usually perceived to move perpendicular to its contours. This "normal motion"

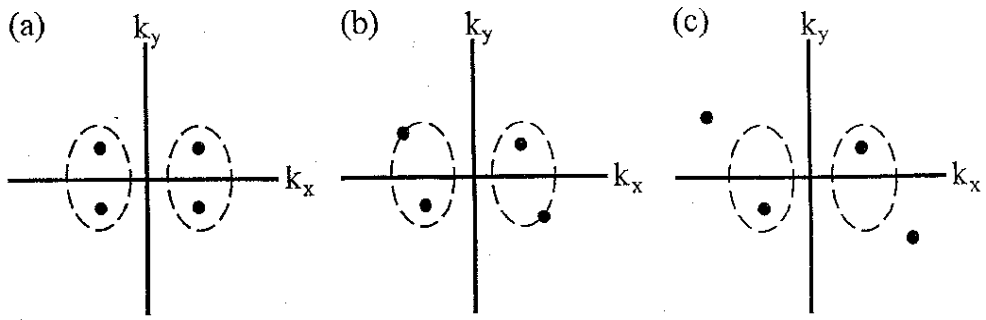

Fig. 3. Schematic diagrams of the power spectra of plaid stimuli in the frequency domain when the magnitudes of the component spatial frequencies are: (a) identical; (b) slightly different; (c) very different. The axes, k_x and k_y, are horizontal and vertical spatial frequency, respectively. The power due to each component is represented by a pair of dots positioned symmetrically about the origin. The distance of each dot from the origin corresponds to the magnitude of the spatial frequency of that component, while its angular position represents the grating's spatial orientation. The position of one pair of dots relative to the other corresponds to the orientation and spatial frequency of the contrast beat produced by the interaction of the two components. The regions contained by the dotted lines represent the passband of a spatial filter processing the image at a particular spatial scale. When the magnitudes of the component spatial frequencies are identical, both components are processed by the same spatial filter. As the spatial frequency of one component increases, the degree to which it activates the original spatial filter decreases until it no longer excites that spatial filter at all. When both components pass through the same spatial filter, linear processing recovers the two components while non-linear processing recovers the contrast beat. When the components pass through different spatial filters, the visual system is insensitive to the contrast beat and only the components are recovered.

is the slowest velocity lying on the constraint line in velocity space. When two sinusoidal components are present at different orientations, their two constraint lines in velocity space intersect, defining a unique "pattern motion". When both components sit in the passband of a single spatial filter, the non-linear channel provides a third constraint line, again passing through the same point of intersection. Thus, in all plaid patterns consisting of two non-parallel sinusoidal components, a unique pattern velocity is defined regardless of the spatial frequencies of the two components. Why, then, do we sometimes perceive plaid motion as transparent?

To explain the fact that gratings of different spatial frequencies do not appear coherent to normal observers, we must propose that motion at different spatial frequencies (and hence different scales) is processed separately until after the stage at which component motions are combined. However, it is clear that there must, at some stage, be interactions between the representations of motion at different scales, as coherent motion can be observed in plaids with spatial frequency ratios well in excess of the bandwidth of a single spatial frequency channel [14]. We propose that the computation of motion coherence and transparency involves two stages beyond the extraction of local motion signals by linear and non-linear channels at a range of scales. At the first stage, interaction between the linear and non-linear channels at the same scale determines the resultant motion at that scale. At the second stage, competition across scales determines the final percept.

The behaviour of a motion processing architecture in which interaction between linear and non-linear channels precedes competition between scales is illustrated schematically in Fig. 4. Each of the three columns contains velocity space representations of three plaid stimuli. In neuronal terms, we can think of each velocity space representation as the pattern of activity across a population of velocity-tuned cells. In the first column, the velocity space representation takes its input from linear and non-linear channels extracting motion at a coarse spatial scale (low spatial frequency), while in the second column the velocity space representations are based upon fine scale (high spatial frequency) motion information. The resultant motions at the different scales then interact competitively to determine whether the overall percept is coherent or transparent. The velocity space representation in which this final interscale competition takes place is shown in the third column. Note that while the human visual system certainly operates at multiple spatial scales, the following discussion is simplified by considering only two scales since each plaid has components at only two spatial frequencies.

The top row of Fig. 4 illustrates the velocity space representations of a plaid stimulus with components of equal spatial frequency oriented at $\pm 30°$ to the vertical (see Fig. 1a–c). Both components are processed at the same spatial scale, giving rise to velocity constraint lines oriented at $\pm 30°$ to the vertical. In addition, processing by the non-linear channel yields a third, horizontal, velocity constraint line. The three constraint lines all meet at a single point, corresponding to vertical motion, which is the resultant at that scale (Fig. 4a). Since there are no components of the stimulus at the other spatial scales (Fig. 4b) the only signal reaching the final stage of competition between scales is for vertical motion (Fig. 4c). Even if there were no appreciable signal from the non-linear channel, the resultant motion would still be defined by the intersection of the velocity constraint lines due to the linear components. Alternatively, if there were only information from the non-linear channel, and none from the linear, the normal motion of the non-linear componen

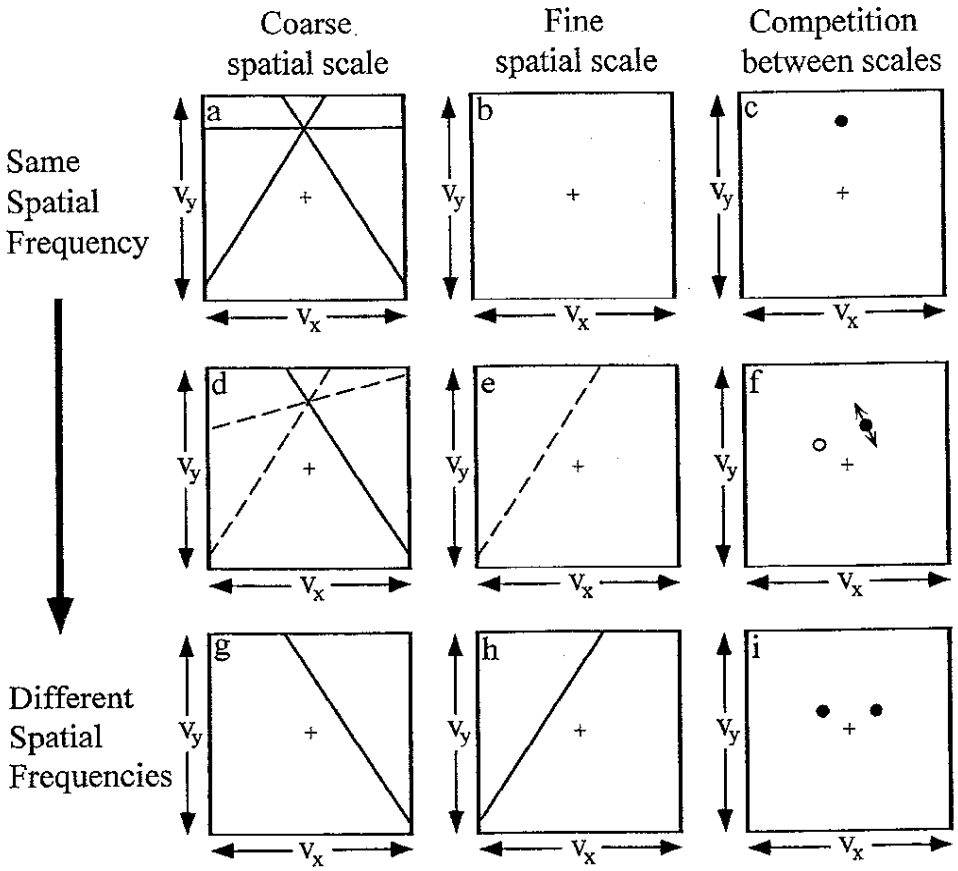

Fig. 4. Velocity space representations of plaid stimuli with component spatial frequencies which are: identical (top row); slightly different (middle row); very different (bottom row). The first and second columns represent the activity of a population of velocity-tuned cells taking input from motion detectors operating at coarse and fine spatial scales respectively. The third column combines information from across scales by taking its input from the first two columns. (a) When the two components have the same spatial frequency, the linear processing of each gives rise to a velocity constraint line at the same spatial scale. The orientation of each constraint line is parallel to the iso-luminance contours of the corresponding grating. The third, horizontal, constraint line is due to the non-linear channel, which recovers the horizontally oriented contrast beats formed by the interaction of the two components. The three constraint lines all meet at a point in velocity space which corresponds to motion in the vertical (IOC) direction. Since there is no excitation of the cells sensitive to motion at fine spatial scales (b), the only signal reaching the final stage of interscale competition is that from the coarse scale, corresponding to vertical pattern motion (c). (d) When the component spatial frequencies are slightly different, the activation of coarse scale cells to the higher spatial frequency grating is reduced, as is the response of the non-linear channel. The presence of the lower spatial frequency component ensures that a significant response still reaches the stage of interscale competition (f), though this no longer necessarily signals motion in the IOC direction. The higher spatial frequency grating will also produce some activation at the fine spatial scale (e), giving rise to a weak signal in the component's normal direction (f). If the component spatial frequencies are very different, each spatial scale will only respond to one of the two components (g,h), giving rise to two distinct peaks in the velocity space histogram (i) and the percept of motion transparency in normal observers.

would still be in the vertical direction. Thus, when the two components of the plaid stimulus have equal spatial frequency, we would expect coherent motion (in the vertical direction) to be perceived even by patients with deficits in linear or non-linear processing, or deficits at fine spatial scales. All of the patients studied do indeed report coherent motion in this condition (see Fig. 2).

The bottom row of Fig. 4 shows the case when the components of the plaid have very different spatial frequencies. The components are processed at different scales, resulting in single velocity constraint lines at the relevant scales and no response from the non-linear channel (Fig. 4gh). Thus, two different signals reach the final stage of interscale competition (Fig. 4i), corresponding to the normal motions of the two components. It has previously been suggested that the number of prominent peaks in the velocity space histogram determines whether motion is perceived as coherent or transparent [13]. Although Wilson and Kim [32] have subsequently argued that bimodality in the velocity space representation is a necessary but not a sufficient condition for motion transparency, they accept that it is a useful heuristic for predicting transparency in many cases.

When the plaid components differ markedly in spatial frequency, normal observers report transparency. However, patient GT reports coherent motion contralesionally even when the ratio of the component spatial frequencies is as high as 2.5. How could such a percept arise from damage to the proposed motion processing architecture? One theoretical possibility is that the motions at different scales

could interact prior to the stage at which multiple velocity constraints are resolved. This would require either that signals at different scales interact earlier than in normal observers, or that velocity constraint lines are propagated to the final stage of processing before resolved, giving rise to IOC across scales. It is not clear whether a specific breakdown in competition at the stage of combination of linear and non-linear motion information might result from a brain lesion. A simpler possibility is that the patients' anomalous perception of coherence is due to a loss of the information from one of the relevant spatial scales prior to interscale competition. In this case the motion of one of the component gratings would capture the other [25], and the patient would report coherent motion. Note that such a deficit would have to occur after the initial stage of motion extraction, as contrast sensitivity for all the patients was normal. A potential way to distinguish between the possibilities of IOC across scales and motion capture would be to ask the patients to report the direction of motion when perceived as coherent. If the response were IOC across scales then motion should appear to be vertical, while in motion capture the direction of motion should correspond to that of the capturing, presumably lower spatial frequency, component. However, the patients in this study were only required to make a coherent/transparent judgement, so coherence could in principle have arisen either from pattern motion or from capture of one component by the other.

We have discussed the two limiting cases: (i) component spatial frequencies are equal and normal observers report coherence; (ii) component spatial frequencies are very different and normal observers perceive transparency. What determines the transition between coherence and transparency as the relative spatial frequency of the components is varied? The case of a plaid with components differing slightly in spatial frequency is illustrated in the middle row of Fig. 4. The spatial frequency of one component remains fixed, giving rise to strong excitation (solid line) in Fig. 4d. Increasing the spatial frequency of the other component weakly excites both coarse and fine spatial scales (dotted lines oriented at 30° to vertical). Increasing the spatial frequency of one component also weakens the response of the non-linear channel and perturbs the corresponding velocity constraint line away from horizontal. This is because the contrast beat is now oriented slightly away from horizontal (see Fig. 3ab). For a normal observer there will be two signals entering the final stage of interscale competition. From the finer spatial scale there will be a weak signal corresponding to the normal motion of the higher spatial frequency component. From the coarser scale there will be a stronger signal from somewhere between the normal direction of the lower frequency component and the IOC direction, depending on the relative strengths of the signals from the components. This is illustrated in Fig. 4f. As the spatial frequency of one component is increased, so the prominence of the corresponding peak in the final velocity space representation increases until the histogram is sufficiently bimodal to generate a percept of transparency.

For normal observers, the transition from coherence to transparency occurs at a relative spatial frequency of around 1.7, slightly lower than would be expected for foveal presentation. However, for patients JK and AMG any departure from 1.0 in relative spatial frequency in the contralesional hemifield causes them to perceive transparent motion. How can these data be accommodated into the proposed model? For transparency to occur we assume it is necessary for the final stage velocity histogram to contain two (or more) peaks of similar prominence. For the coherence/transparency transition to occur at a lower spatial frequency than in normals, either the signal from the coarser spatial scale must be weakened or that from the finer scale strengthened. It is more intuitive to think of a brain lesion as weakening a particular pathway, but we cannot rule out the possibility that weakened activity in one pathway will reduce inhibition of another pathway and thus increase signal strength there. Perhaps the coarse spatial scale is providing a weaker signal to the final stage of interscale inhibition. This could arise for one of two reasons. Either processing at the coarser spatial scale is affected by the lesion, or the input from the non-linear channel has been disrupted. In the latter case the signal from the coarser scale pathway would be correspondingly weakened, and would be more likely to reflect the normal motion of the lower frequency component (as in Fig. 4g) than the IOC velocity (as in Fig. 4a).

What of patient RA? For him the transition point from coherence to transparency comes at around 2.0 cycle/deg, as opposed to 1.7 cycle/deg for normal observers, which is mildly anomalous. Patient RA is of interest as his perceptual deficits can be modelled by weakening the contribution of the linear channel in a two-channel model of motion processing [6,29]. Let us consider the effect of weakening the contribution of the linear channel on the perception of plaid motion. Clearly the relative contribution of the non-linear pathway will be more significant, so while there is even a weak non-linear signal this can be expected to dominate over what response there is from the linear channel. Thus the perceived motion of the plaid will correspond to the normal motion of the non-linear component. However, once the spatial frequencies of the two components are sufficiently different that they no longer pass through filters at the same spatial scale, there will be no response from the non-linear channel and transparency will be perceived on the basis of the (weakly signalled) normal motions of the two linear components (as in Fig. 4g–i). Thus we might expect a patient with damage to the linear channel to perceive transparency at the highest spatial frequency ratios, but for the transition from coherence to transparency to occur at a higher relative spatial frequency than for normals. This is indeed what we observe in the data of RA.

6. General discussion

The conditions under which plaid motion is perceived as coherent or transparent provide insight into the processes underlying the perception of coherent and transparent motion. One theory is that motion transparency relies on the perceptual grouping of image attributes [16]. Several computational models of plaid coherence and transparency effectively group regions of the image together on the basis of their motion [12,13,19,20]. The Heeger and Jasinschi models construct velocity histograms corresponding to all the component motions consistent with the spatiotemporal variation in image intensity, and then classify the motion as coherent or transparent depending whether there is a single peak or multiple peaks in the velocity histogram. The filter selection approach of Nowlan and Sejnowski [20] coarsely segments an image into regions of coherent motion that represent distinct objects moving with common velocities. The number of regions selected by the model determines whether motion is perceived as globally coherent, or whether the image is divided into occluding or transparently moving objects.

An alternative suggestion to the idea of perceptual grouping is that our visual systems embody tacit knowledge about the physics of transparency [26]. If the visual system does employ implicit knowledge of motion transparency, then what determines when a coherent interpretation of image motion dominates over transparency, and vice versa? One way of viewing the ascription of coherence and transparency to a region of image is as a competition between alternative models [15]. A plaid pattern can be considered as the additive superposition of two gratings. In the case of (co)sinusoidal gratings, an equivalent multiplicative decomposition of the plaid exists by virtue of the trigonometrical identity:

$$\cos(\alpha) + \cos(\beta) = 2\cos\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{\alpha-\beta}{2}\right).$$

Langley [15] proposes that the models employed by the visual system correspond to the alternative additive and multiplicative decompositions of a plaid pattern into its sinusoidal components. The additive (linear) decomposition corresponds to transparency over scale, while the multiplicative (non-linear) model recovers the pattern motion [9].

Strong psychophysical evidence for the presence of linear and non-linear motion processing channels operating at multiple spatial scales has recently been forwarded by Nishida et al. [18]. They used selective adaptation to show that direction identification thresholds for both first- and second-order motion are spatial frequency selective, while cross-over adaptation effects between the two classes of stimuli are weak and show no spatial frequency tuning. The existence of linear and non-linear motion pathways is also suggested by the physiology. As evidence of non-linear processing, direction selective neurons sensitive to motion defined by non-luminance cues have been reported in primate [2,21–23] and cat [33,34]. In response to plaid stimuli, neurons have been found which respond preferentially to component motion, consistent with the expected properties of the linear channel, while others signal the

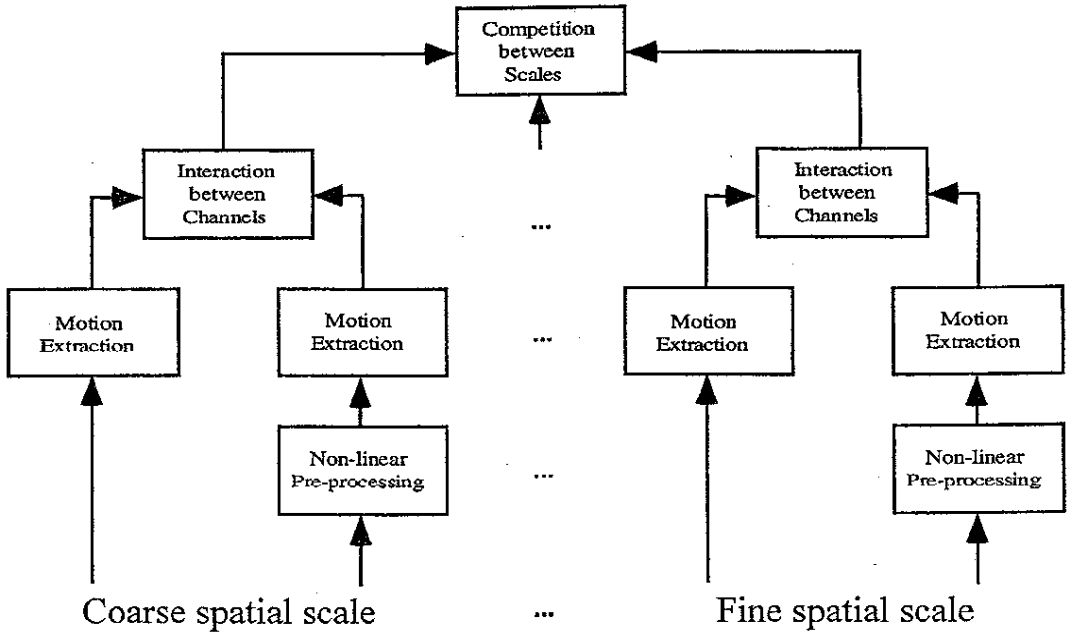

Fig. 5. Schematic representation of the parallel processes proposed to underlie the perception of motion coherence and motion transparency. Spatial filters decompose the image into signals at a range of spatial scales. At each scale processing is carried out by parallel linear and non-linear channels. The responses of these channels interact at each spatial scale. Finally, the responses from the individual scales are combined into a velocity space histogram. The form of the histogram determines whether motion is perceived as coherent or transparent.

coherent motion of the plaid pattern, suggesting a role later in processing after the combination of component signals [10,17].

Some of the most compelling evidence for distinct linear and non-linear motion mechanisms comes from the study of neurological patients. Plant and Nakayama [24] reported selective impairment to motion from contrast cues in the visual hemifield contralateral to unilateral posterior cerebral lesions in three patients. Greenlee and Smith [11] described three patients with superior temporal or lateral inferoparietal lesions who had much higher threshold elevations for speed discriminations based on luminance than non-luminance cues. Vaina and Cowey [27] reported the case of a patient, FD, who had a marked contralesional deficit in his perception of motion defined by non-luminance cues, but no impairment with corresponding luminance-defined motion stimuli. Vaina et al. [29] reported that patient RA, also studied here, showed a deficit only in the perception of luminance-defined motion. Taken together, the visual deficits of patients FD and RA constitute a double dissociation of function between the processing of motion defined by luminance and non-luminance cues, which can be modelled by selectively impairing elements of parallel linear and non-linear motion pathways [6].

Our data suggest a motion processing architecture in which linear and non-linear channels are present at multiple scales. The pairs of channels interact at each scale, and the outputs from each scale are then combined in a further stage of competition (Fig. 5). The existence of parallel linear and non-linear motion pathways was originally proposed by Chubb and Sperling [4,5] to account for the ability of the human visual system to perceive motion defined by non-luminance cues (such as contrast and flicker) in addition to luminance-based motion, and the idea has been extended by Wilson et al. to model the perception of plaid motion [14,31,32]. The model we propose is consistent with the data from patient CS, who has lower direction discrimination thresholds for plaids than for their constituent gratings [30]. CS's direction discrimination performance is not consistent with the IOC model, which predicts that errors in discriminating the direction of the component gratings would be compounded for plaid motion, resulting in higher direction discrimination thresholds for plaids than for individual gratings. However, CS's data is consistent with a model in which the outputs of linear and non-linear motion pathways are combined in discriminating the direction of plaid motion, since component directions are recovered by the linear channel while information on the direction of plaid pattern motion is contained in the outputs of both channels. Thus, an impairment to the linear channel would be expected to affect judgements of component direction more severely than pattern direction discrimination thresholds.

While Nishida et al. [18] provide psychophysical evidence for distinct linear and non-linear motion pathways, the motion processing architecture they forward differs from that proposed here as they argue for integration over spatial scale prior to the combination of signals from the linear and non-linear pathways. They cite the finding of Edwards and Badcock [7] that the presence of second-order noise dots does not impair the extraction of the global motion of first-order dots, taking the result as evidence that the linear and non-linear channels remain separate up to and including the level of global motion extraction. However, since random dot kinematograms are broad band stimuli, it is probable that pre-processing in the non-linear channel affects the relative strengths of the signals from the first- and second-order channels. If there is a spatial scale at which the signal from the non-linear channel is weaker than the signal from the linear channel, then selective attention to that scale would enable the second-order noise dots to be ignored and the global motion of the first-order dots to be extracted. Thus, the results of Edwards and Badcock [7] do not necessarily imply that there can be no interaction between the linear and non-linear motion pathways prior to the integration across scales. A possible way to explore this issue further would be to isolate individual spatial scales by investigating the effect of band-pass filtering random dot stimuli.

7. Summary

We have investigated the perception of coherent and transparent motion in plaid patterns in four neurological patients and five normal controls as a function of the relative spatial frequency of the two components. Keeping the spatial frequency of one component fixed at 1.0 cycle/deg, we find that normal subjects perceive coherent motion at least 75% of the time for relative spatial frequencies of 0.75–1.75. Two of the patients we studied (JK and AMG) perceived coherence in the contralesional field only when the component spatial frequencies were almost identical, while the others (GT and RA) reported coherent motion over a wider range than normals. Our proposed motion processing architecture closely resembles the Wilson et al. [31] model, and can also be seen as an extension of the model used by Clifford and Vaina [6] to simulate selective deficits in motion perception defined by luminance or non-luminance cues. The notion of competition between coherent and transparent interpretations of image motion is consistent with the model-based approach put forward by Langley [15].

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