PERGAMON

Vision Research 39 (1999) 2999–3009

Vision Research

www.elsevier.com/locate/visres

Section 2

Non-veridical size perception of expanding and contracting objects

David Whitaker *, Paul V. McGraw, Sarah Pearson

Department of Optometry, University of Bradford, Richmond Road, Bradford BD7 1DP, UK

Received 26 August 1998; received in revised form 14 December 1998

Abstract

Observers were presented with various types of stimulus expansion and contraction which resulted in marked misperceptions of size. Firstly, the perceived size of an object which is changing in size is shown to be biased in the direction of the size change. Secondly, expansion or contraction of the internal texture of objects is found to influence their perceived size. Finally, an illusory texture manipulation in the form of a movement after-effect is shown to produce the same type of size misperception as a real expansion or contraction of internal texture. The spatio-temporal characteristics of these illusory size changes are investigated.
© 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Size; Motion; Illusion; After-effect; Human

1. Introduction

The human visual system is regularly presented with stimuli which are undergoing optical expansion or contraction. This can occur either due to objects physically approaching or receding, or it can occur due to self-locomotion through the visual environment. Optical changes of this kind (in particular optical expansions) are a potent indicator of potential danger and often signal the need for evasive action. It might, therefore be expected that the human visual system has developed both precise and veridical means of quantifying the spatial characteristics of optically expanding and contracting objects. In this paper we show that, whilst being precise, such judgements are often far from veridical.

It is known that observers misperceive the location of objects which are undergoing motion in the fronto-parallel plane. Specifically, the true instantaneous location of an object lags behind perceived location by some considerable distance (Foster & Gravano, 1982; Freyd & Finke, 1984; Nijhawan, 1994). Nijhawan (1994), for example, presented a rotating stimulus consisting of both continuously moving elements and briefly flashed elements, the latter appearing in true physical alignment with the continuous elements. Despite this, the continuously moving part of the stimulus was perceived to be ahead of the flashed elements. Foster and Gravano (1982) and Freyd and Finke (1984) report experiments where a sequence of frames of apparent movement are presented and the subject is required to judge the spatial location of the final frame. Observers consistently overestimate final position in the direction of implied motion. The term representational momentum (Freyd & Finke, 1984) has been applied to this phenomenon, reflecting a cognitive assignment of momentum to the internal representation of the object, analogous to physical momentum of objects which, in the real world, tends to keep them in motion along the same path in which they are currently travelling. In the present study we investigate whether this misperception of spatial position carries over to a misperception of the instantaneous size of objects undergoing continuous motion in the form of expansion or contraction.

Spatial and temporal misperceptions are often termed illusions. Several geometric illusions stem from the fact that visual information provided by the second-order statistics (texture) of objects is in conflict with that from the stimulus envelope as a whole. The Fraser twisted

---

* Corresponding author. Fax: +44-1274-385570.
E-mail address: d.j.whitaker@bradford.ac.uk (D. Whitaker)

0042-6989/99/$ - see front matter © 1999 Elsevier Science Ltd. All rights reserved.
PII: S0042-6989(99)00010-3

cords illusion is an ideal example (Fig. 1). The figure consists of vertical lines defined by variations of contrast. The texture contrast itself is, however, not oriented vertically, but obliquely in alternate lines, giving the lines themselves the impression of slant. This may be viewed as a general situation in which the spatial nature of objects can be biased by unusual and unexpected variations in texture (Morgan & Baldassi, 1997).

In the case of optical expansion and contraction of real-world objects, not only does the absolute size of the object either increase or decrease (a global change), but the texture within the object (if present) also undergoes expansion or contraction (local change). What happens to perceived object size if there is a mismatch between local and global visual information in the form of expansion or contraction? In the case of lateral spatial position, we know that this situation can result in unusual spatial misperceptions. Several studies (Regan & Beverley, 1984; Ramachandran & Anstis, 1990; De Valois & De Valois, 1991) have noted that the lateral motion of texture within a patch produces a strong misperception of the spatial position of the patch in the direction of motion. Ramachandran and Anstis (1990) extended this finding by demonstrating that the radial motion of random dots within annular stimuli biased the perceived size of the annuli in the direction of the motion of the dots. In the present study we quantify the illusory size misperceptions of expanding and contracting textured stimuli in spatio-temporal terms. Finally, we present an unusual example of an illusory size change which is itself the result of an illusory expansion or contraction.

2. Experiment 1

2.1. Methods

2.1.1. Stimuli

Generation and control of stimuli was performed using the macro capabilities of the public domain software NIH Image™1.61 (developed at the US National Institutes of Health and available from the Internet by anonymous FTP from zippy.nimh.nih.gov or on floppy disk from the National Technical Information Service, Springfield, Virginia, part number PB95-500195GEI). Stimuli were presented on a Mitsubishi 21″ d2 Colour Display Monitor with a mean luminance, L, of 38.3 cd m^{-2} and a frame rate of 75 Hz. The non-linear luminance response of the display was linearised by using the inverse function of the luminance response as measured with a Minolta CS-100 photometer. The host computer was a Motorola Starmax 4000/200 PowerPC. The stimuli (shown in Fig. 2) were radial luminance gratings windowed by a two-dimensional Gaussian (radial Gabors). Their mathematical description is

$$L+\left[\exp\frac{-(x^2+y^2)}{2\sigma^2}\{LC(\sin((2\pi F\sqrt{x^2+y^2})+\phi))\}\right] \tag{1}$$

where x and y are the respective horizontal and vertical distances from the centre of the stimulus, F and C are the respective spatial frequency and contrast of the radial grating, ϕ is a phase increment, and σ is the standard deviation of the Gaussian window.

2.1.2. Subjects

The authors acted as observers, having undertaken several practice sessions prior to data collection. Observers viewed the screen monocularly from a distance of 70 cm and wore their optimal distance spectacle correction (where appropriate) for all stimulus conditions. Data were collected under conditions of dim room illumination.

2.1.3. Procedure

On any given trial, two radial Gabor stimuli were presented, separated by a centre-to-centre distance of 6° of visual angle (Fig. 2). The right hand one of these was always static ($\sigma = 0.5°$) whilst the other was made to either expand or contract on any given trial. Note that the Gabors changed in size equally in every dimension, both in terms of carrier and Gaussian window. During trials in which expansion occurred, the expanding radial Gabor would start at approximately half the size of the static Gabor and then begin expanding logarithmically until, at a certain point, both stimuli disappeared. Subjects were asked to fixate between the radial Gabors (the provision of a fixation point was found not to be necessary) and to compare the size of the moving Gabor with that of the static Gabor at the point of disappearance. Subjects responded as to which stimulus

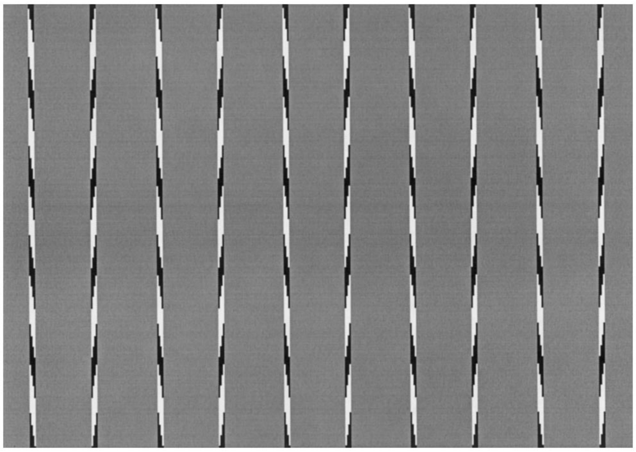

Fig. 1. The lines of the Fraser twisted cords illusion appear slanted due to the oblique orientation of the texture contrast within the lines. Such a misperception or illusion can occur when the visual information given by the texture properties of a stimulus is discordant with that provided by the stimulus envelope.

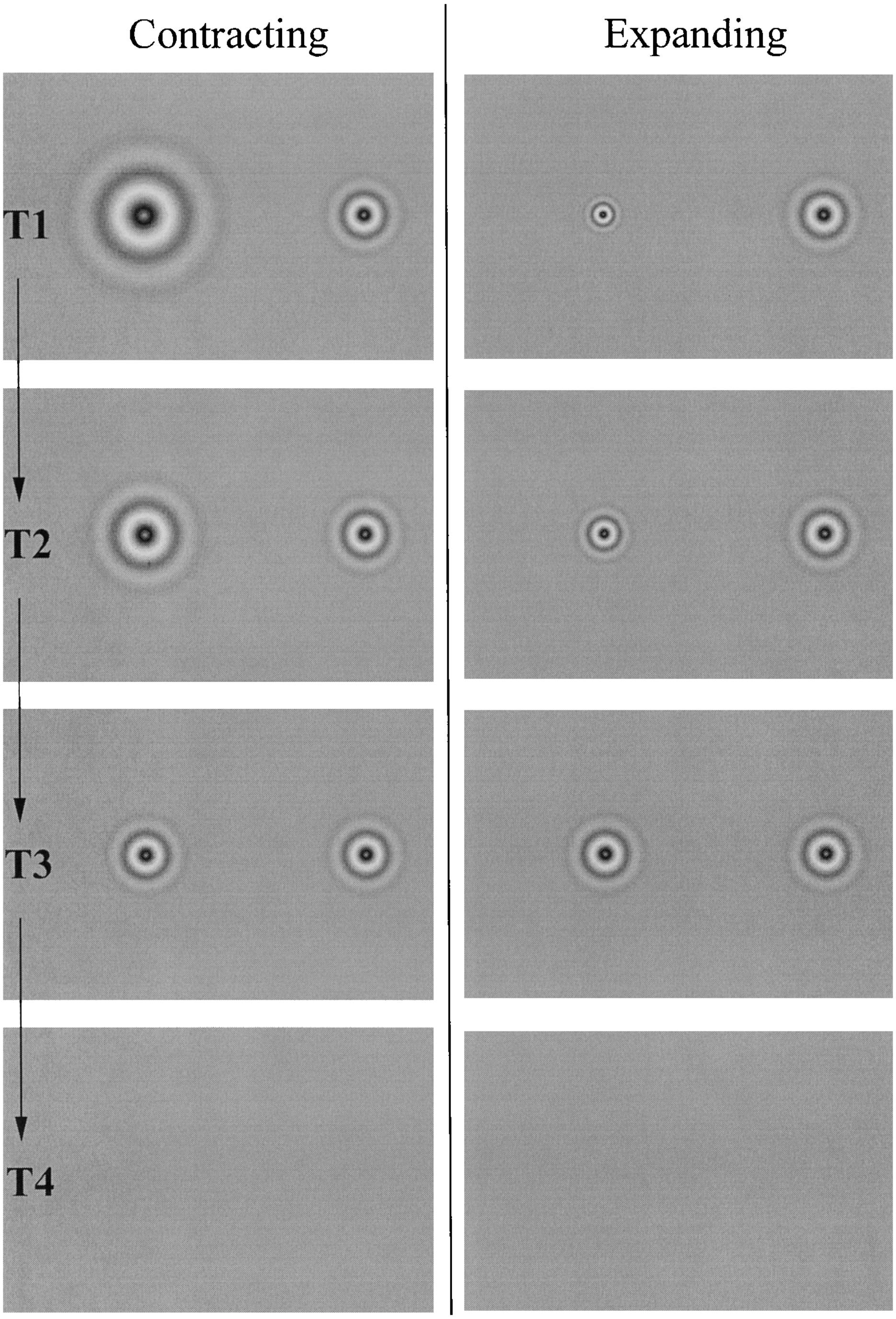

Fig. 2. Examples of the stimuli used in Experiment 1. The series of panels on the left-hand side of the figure depicts a time sequence involving a contracting radial Gabor. A static, reference radial Gabor is presented to the right of the contracting stimulus. At the beginning of the trial, T1, the moving Gabor is approximately twice the size of the static stimulus. The moving Gabor then contracts in logarithmic fashion at a pre-determined rate until it reaches a size similar to that of the static Gabor (T3) at which time the stimuli are replaced by a blank field (T4). The subject is then required to indicate whether the final size of the moving Gabor was larger or smaller than the static stimulus. The right-hand series of panels depict the same situation for an expanding stimulus.

appeared larger via the computer keyboard. During trials in which contraction occurred, the contracting radial Gabor would start at approximately twice the size of the static Gabor and begin contracting logarithmically until the disappearance point. Note that we quantify size in linear terms, i.e. the linear standard deviation of the Gaussian envelope. Either expansion or contraction could occur randomly on any trial. Further, to prevent a timing cue being used, starting sizes were subject to a random variation of up to 0.125 log units.

On any trial, both stimuli were made to disappear once the expanding or contracting stimulus reached one of seven possible sizes relative to the static stimulus. 20 trials were run at each of these seven sizes for both expansion and contraction. The first ten trials of the run were discarded, meaning that a total of 290 trials were necessary to obtain a full data set. From the resulting data, the size of the expanding or contracting stimulus which appeared the same size as the static stimulus was calculated.

The rate of expansion or contraction was quantified by a time constant which represents the time taken for the moving stimuli to either double or halve in size. Time constants of 0.375, 0.75, 1.5 and 3 s were investigated. Radial spatial frequencies of 0.5, 1 and 2 c/deg were used.

2.2. Results

Fig. 3 shows a typical data set. The percentage of larger responses are plotted as a function of the size of the expanding or contracting stimulus at the disappearance point expressed relative to the size of the static reference radial Gabor. Relative sizes greater than 0 log units mean that the expanding or contracting stimulus was physically larger than the static stimulus at the disappearance point. As would be expected, the proportion of larger responses increases as the physical size of the moving stimulus at disappearance increases. This occurs for both the expanding stimuli (□) and for the contracting stimuli (■). However, the functions for the two types of movement are separated from one another, with the contracting stimuli requiring considerably larger physical sizes in order to produce the same proportion of larger responses as the expanding stimuli.

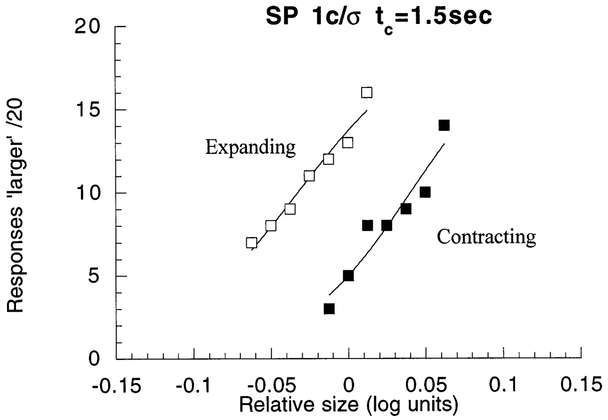

Fig. 3. The percentage of times the observer responded that the moving Gabor appeared ‘larger’ than the reference plotted against the actual relative size of the moving Gabor at its disappearance point. The data illustrate how the number of ‘larger’ responses increase as the relative size of the moving Gabor increases, but that the functions for expanding (□) and contracting stimuli (■) remain separated along the size axis. This indicates that contracting stimuli need to be made larger than expanding stimuli at the disappearance point in order to be perceived as the same size. In this case (spatial frequency of 1 c/deg and a time constant of 1.5 s) the magnitude of the illusion is 0.0728 log units, or 18.2%.

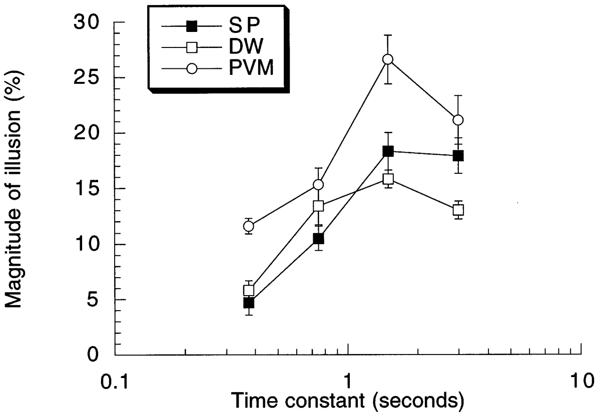

Fig. 4. The magnitude of the illusion (the percentage overestimation of the size of the expanding stimuli relative to contracting stimuli) plotted against the time constant of expansion or contraction for three observers. Radial spatial frequency was 1 c/deg. The illusion is smallest at the shortest time constant (when the stimuli are expanding or contracting most rapidly) and peaks at about 1.5 s.

A method of least squares was used to fit each data set with a logistic function of the form

$$y=\frac{100}{(1+e^{\wedge((k1-x)/k2)})} \tag{2}$$

where $k1$ is the relative size corresponding to 50% larger responses and $k2$ provides an estimate of the slope of the function, representing half the relative size difference between 26.9 and 73.1% larger responses.

In Fig. 3, $k1$ for the expanding stimulus is -0.0325 whilst for the contracting stimulus it is 0.0403. This means that an expanding stimulus of $10 \wedge^{(-0.0325)} = 0.928$ times the size of the reference stimulus was perceived as being equal in size to the reference. In other words the perceived size of the expanding stimulus is overestimated by 7.2%. A contracting stimulus of $10 \wedge^{(0.0403)} = 1.097$ times the size of the reference stimulus was perceived as being equal in size, a perceived underestimation of 9.7%. The relative difference in perceived size of the contracting and expanding stimuli is given by $10 \wedge^{(0.0403-0.0325)} = 1.182$, i.e. an overestimation of the size of the expanding relative to the contracting stimulus of 18.2%.

Fig. 4 shows the percentage overestimation in the size of expanding relative to contracting stimuli as a function of the time constant. Radial spatial frequency was 1 cycle/σ. For all observers the size of the illusion is smallest for the most rapidly expanding and contracting stimuli and reaches a peak at a time constant of around 1.5 s. Fig. 5 shows the effect of varying radial spatial frequency for a fixed time constant of 1.5 s. For all observers the size of the illusion is smallest at low spatial frequencies and peaks at around 1 cycle/σ.

3. Experiment 2

3.1. Methods

3.1.1. Stimuli

The stimuli in this experiment were again radial Gabors but, instead of the Gabors increasing or decreasing in overall size, the Gaussian envelope remained a constant size during any trial, and the radial carrier grating was made to drift outwards (expanding) or inwards (contracting). However, the spatial frequency of the radial grating remained constant such that there was neither magnification nor minification of the stimulus, simply a systematic phase drift of the carrier grating within a fixed window. Stimulus spatial frequencies of 1–8 c/deg and temporal frequencies of 0.6–4.8 Hz were investigated.

3.1.2. Procedure

On any given trial a single radial Gabor was presented whose carrier grating was randomly chosen to be expanding or contracting (Fig. 6). The size of the Gaussian window (defined by σ) within which the carrier grating drifted was chosen randomly from one of six possible sizes, each differing by 0.025 log units. These sizes were chosen on the basis of preliminary pilot experiments. No stationary reference Gabor was provided. Instead, the perceived size of the single Gabor was judged relative to the ensemble of all the previously presented stimuli, i.e. the subjects constructed an internal size representation against which they could compare the perceived size of any subsequently presented stimulus. After ten initial trials which served to build an internal representation of the mean, 20 presentations were made at each of the six stimulus sizes for both expanding and contracting stimuli, meaning that a total of 250 trials were necessary to obtain a full data set.

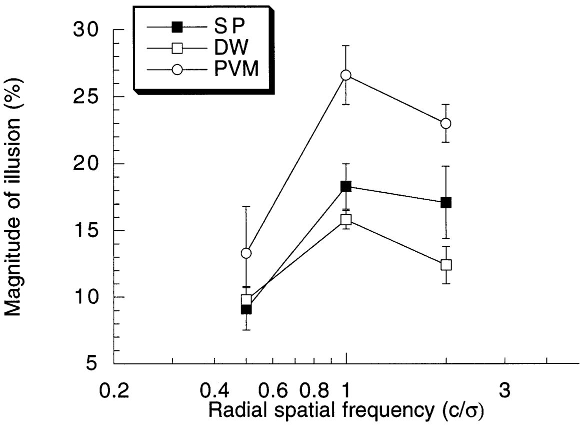

Fig. 5. The magnitude of the illusion as a function of the radial spatial frequency of the Gabor stimuli. The time constant of expansion or contraction was 1.5 s. The illusion peaks at a radial spatial frequency of 1 c/deg and reduces at higher or lower frequencies.

3.2. Results

Fig. 7 shows example data for a single observer and a single spatio-temporal condition (2 c/deg and 2.4 Hz). The percentage of larger responses are plotted against the physical size of the stimuli relative to the mean of the ensemble. As would be expected, as the physical size of both expanding and contracting stimuli increases, the probability that they are perceived as larger increases. However, the data for the expanding and contracting stimuli are separated from one another along the size axis, indicating that stimuli of quite different physical sizes are perceived as being identical in size. Specifically, stimuli whose carrier grating is drifting outwards (expanding) require smaller window sizes to be perceived as equivalent to stimuli whose carrier grating is drifting inwards. In other words, expanding stimuli are perceived as larger than contracting ones, despite equivalence in their physical dimensions. The data are fitted with a logistic function of the form given in Eq. (2). The extent of the size misperception can be quantified by comparing the $k1$ values (size corresponding to 50% larger responses) for the two types of stimuli. For the expanding stimulus, $k1$ was -0.0292, whereas for the contracting stimulus it was 0.0352. The relative difference in perceived size of the contracting and expanding stimuli is given by $10 \wedge^{(0.0352-0.0292)} = 1.160$, i.e. an overestimation of the size of the expanding relative to the contracting stimulus of 16.0%. Also shown in the Figure are data for judging the relative size of statically presented radial Gabors. These data, which were gathered separately, fall approximately mid-way between the expanding and contracting data. The significance of this static data set will be addressed in Section 5.

The perceptual size of the illusion can be put into context by comparing it with the thresholds for detecting a change in size for a given type of stimulus. In Fig. 7, size thresholds for both expanding and contracting stimuli are approximately 0.0127 log units. In comparison, the magnitude of the illusion is 0.0644 log units, approximately five times the threshold.

The effect of varying the spatial and temporal frequency characteristics of the stimuli is depicted in 3-dimensional form in Fig. 8. The size of the illusion increases as temporal frequency increases and spatial frequency decreases. This suggests that velocity governs the magnitude of the illusion, and this is confirmed in Fig. 9 where the spatial and temporal conditions have been combined in terms of velocity. Although the data are reasonably well described by a

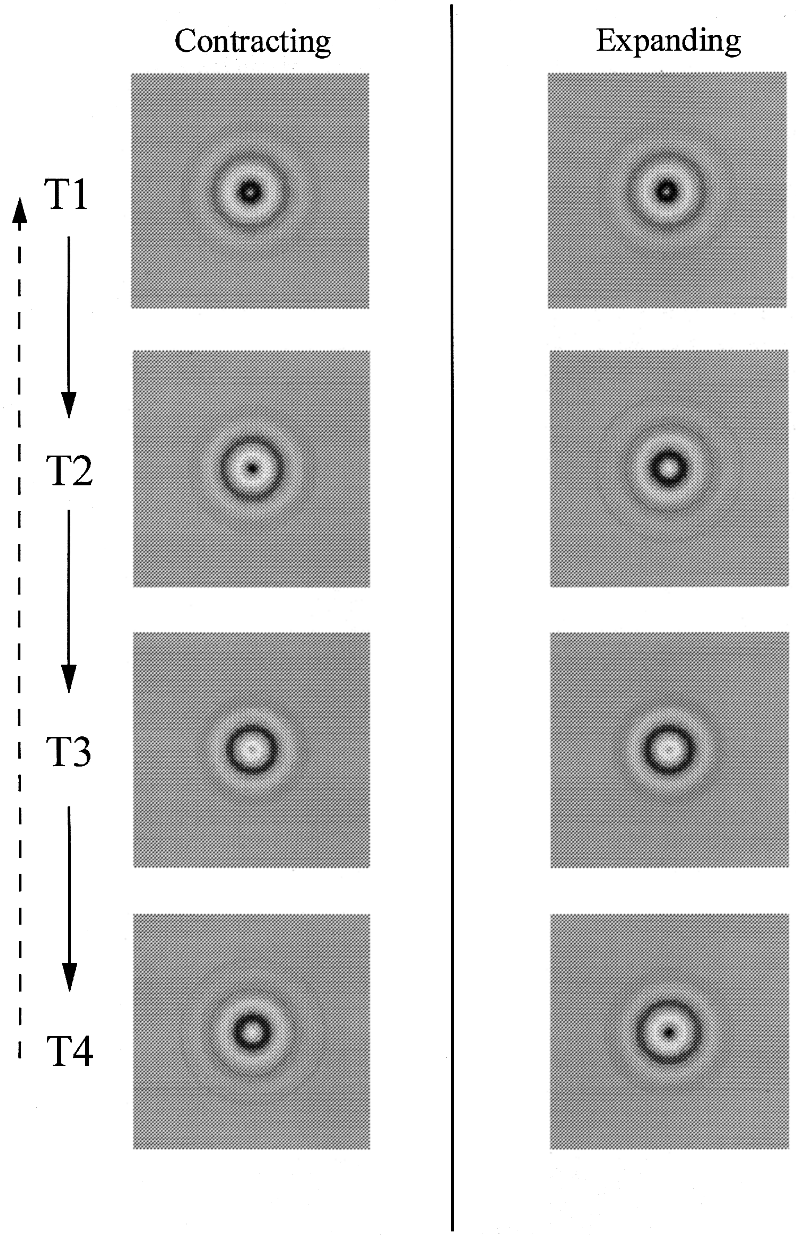

Fig. 6. The stimuli used in Experiment 2. Single radial Gabors were presented, and, instead of the whole stimuli undergoing magnification or minification, the carrier grating underwent contraction (left-hand panels) or expansion (right-hand panels) within the stationary Gaussian contrast envelope. T1-T4 represent the appearance of the stimuli at four equally spaced time intervals within a single cycle of expansion or contraction. The motion of the carrier grating was continuous, i.e. T1 followed on from T4, until the observer made a response. The observer was required to judge the overall size of the stimuli relative to the mean of all the expanding or contracting stimuli which had previously been presented. During a single run, responses were gathered for a series of expanding and contracting stimuli of different sizes.

linear relationship between velocity and the magnitude of the illusion, such a relationship predicts a significant illusion even when the stimuli are stationary (velocity = 0), a situation which is clearly not possible. For this reason a power function has been fitted to the data, implying that the magnitude of the illusion is a saturating function of velocity. It can be seen that the illusion can be well described, at least over the range investigated here, as being proportional to the square root (approximately) of velocity.

4. Experiment 3

4.1. Methods

4.1.1. Stimuli

The stimuli in this experiment were again radial Gabors whose carrier grating underwent expansion or contraction within a contrast envelope of fixed size. Spatial and temporal frequency were kept constant at 2 c/deg and 3 Hz, respectively.

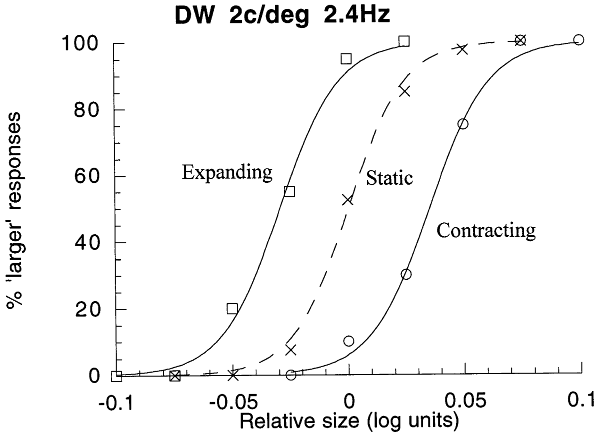

Fig. 7. An example of data gathered from Experiment 2. The percentage of times the observer responded that the moving Gabor appeared larger than the mean size of the all the stimuli presented. The data illustrate how the number of larger responses increase as the actual size (established relative to the mean) of the moving Gabor increases, but that the functions for expanding (open squares) and contracting stimuli (open circles) remain separated along the size axis. In other words, stimuli whose carrier is expanding require a smaller envelope size to be perceived as equivalent in size to a stimuli whose carrier is contracting. In this case (spatial frequency 2 c/deg, temporal frequency 2.4 Hz) the magnitude of the illusion is 0.0644 log units, or 16.0%. Data were also gathered separately for judging the relative size of static radial Gabors (crosses).

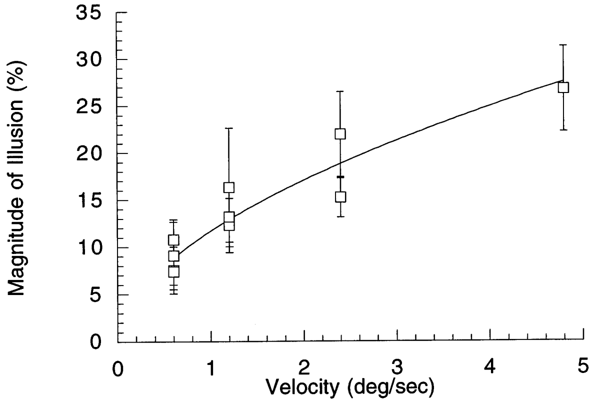

Fig. 9. The data of Fig. 8 plotted in terms of the velocity of expansion or contraction of the carrier grating. As predicted from Fig. 8, the magnitude of the illusion increases with velocity. Each data point represents the mean illusion for three observers, and standard errors are shown. The function $y = 11.67x^{0.546}$ is shown fitted to the data, indicating that the size of the illusion is approximately proportional to the square root of velocity.

4.1.2. Procedure

Two radial Gabors were presented with a horizontal separation of 6° (Fig. 10). A small fixation dot was presented midway between the two Gabors. Each trial consisted of an adapting and a test phase. During the 1.4 s adaptation phase, the left hand Gabor underwent contraction whilst the right hand Gabor underwent expansion. The duration of the adapting phase was chosen on the basis of pilot experiments in which little increase in adaptation effect was found using longer durations. The test phase followed immediately and consisted of a 1 s presentation of two stationary radial Gabors. However, the motion experienced during the adapting phase produced a motion after-effect in the static Gabors such that the right-hand Gabor appeared to contract whilst the left-hand one expanded (an after-effect of expansion and contraction has previously been reported by Regan and Beverley (1978)). The illusory motion resulted in a misperception of size during the static test phase in much the same way as real motion described in Experiment 2. The relative sizes of the Gaussian windows of the radial Gabors presented during the static phase could be varied in order null the actual size illusion. Specifically, the left-hand Gabor

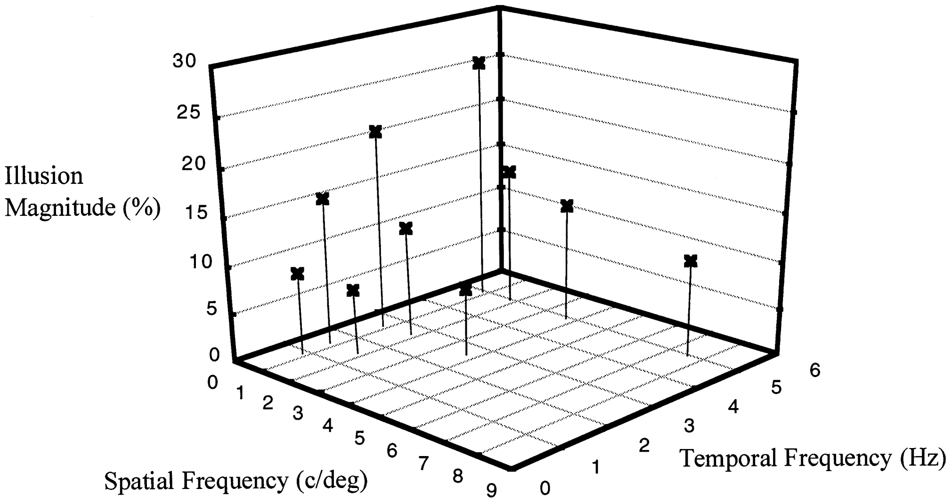

Fig. 8. A 3-dimensional plot to show the effects of varying the spatial and temporal properties of the stimuli on the magnitude of the size illusion. Each data point represents the mean illusion for three observers. The illusion reaches a maximum at high temporal and low spatial frequencies, suggesting that stimulus velocity governs the illusion.

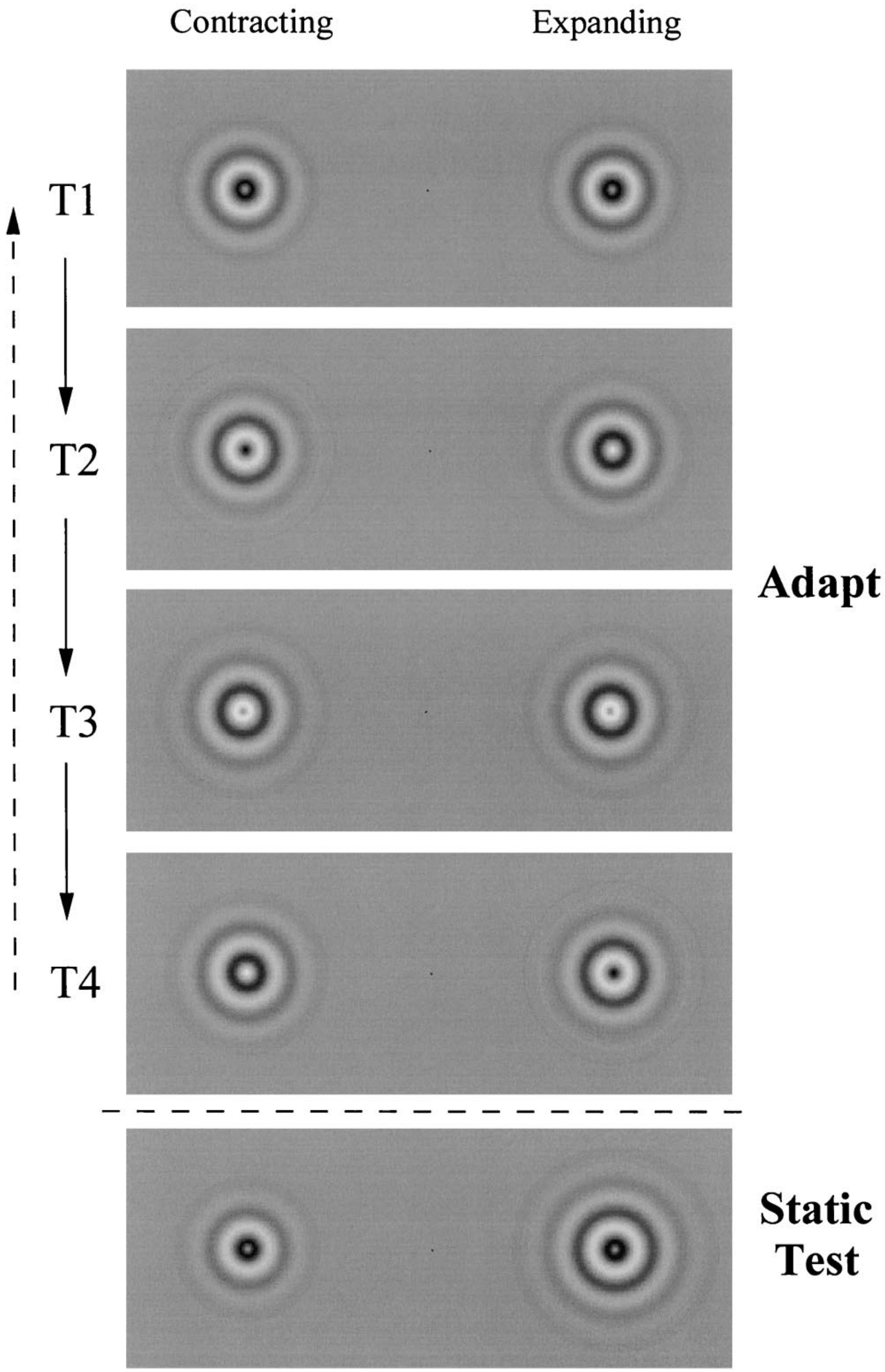

Fig. 10. Stimulus arrangement used in Experiment 3. During an adaptation phase, subjects fixate mid-way between two radial Gabors. The carrier grating within the left-had Gabor was made to contract, whilst in the right-had Gabor it was made to expand. Panels T1-T4 represent the appearance of the stimuli at four equally spaced time intervals within a single cycle of expansion and contraction. The motion of the carrier grating was continuous, i.e. T1 followed on from T4, until the end of the 1.4 s adaptation phase was reached. There immediately followed a static test stimulus consisting of two Gabors whose relative size was chosen from a bank of pre-determined levels. The adaptation produced a movement after-effect within the static test stimuli such that the right-hand Gabor appeared to contract and the left-had one appeared to expand. This illusory movement itself produced a size misperception in the test stimuli, meaning that the right-hand static Gabor had to be made considerably larger than the left-hand one in order to appear perceptually equivalent.

which was perceived as expanding had to be made smaller whilst the right-hand Gabor which was perceived as contracting had to be made larger (see lower panel of Fig. 10). A method of constant stimuli was adopted in which the observer had to respond via the keyboard as to which Gabor appeared larger, left or right. Seven size difference levels were tested, ranging from 0 to 0.130 log units difference in size. One consequence of this method is that the larger static test Gabor becomes somewhat larger than the size of the adapting stimulus (Fig. 10). At the extreme, the size difference amounts to 0.065 log units (around 16%). Whilst this may have reduced the adaptation effect to some extent, we are more concerned with the existence of the effect rather than its quantitative level. Immediately following the observer response the adapting phase began again. Ten initial trials were allowed in order for the observers to familiarise themselves with the task and to allow the magnitude of the motion after-effect to stabilise. Following this, 20 trials were run at each of the seven possible size difference levels.

4.2. Results

Fig. 11 shows the percentage of times the subject responded that the right-hand Gabor appeared larger as a function of the size difference between the left and right-hand Gabors during the test phase. When the size difference is zero or only very small, observers consistently respond that the right-hand Gabor appears smaller, since this is the stimulus which appears to be contracting due to the motion after-effect. As the right-hand Gabor is made physically larger in relative terms, a point is reached at which the two stimuli appear equal in size. In this case (subject DW) equality in perceived size was reached once the size difference reached 0.0579 log units, or 14.3%. Similar values were obtained for the other two observers-SP (15.32%) and PVM (13.74%).

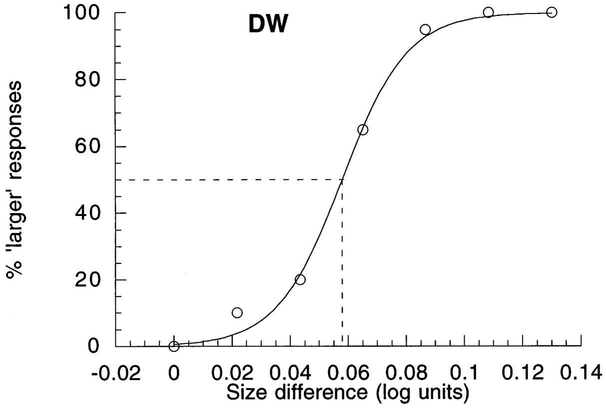

Fig. 11. Data from Experiment 3. Percentage of responses in which the right-hand test Gabor appeared larger as a function of the actual size difference between the right- and left-hand radial Gabors. When the size difference is zero, i.e. the two Gabors are identical in size, the left-hand Gabor invariably appeared larger due to the illusory movement produced by the adaptation phase. Only when the right-hand Gabor is made substantially larger than the left does it consistently appear to be larger. A logistic function is fitted to the data set indicating that the right-hand Gabor had to be made 0.058 log units larger than the left-hand Gabor in order to be perceived as identical in size. This corresponds to an illusion of 14.3%. Subject DW.

5. Discussion

Our results represent observations on the perceived size of two very different types of expansion or contraction, both of which result in marked size misperceptions. The type of motion presented in Experiment 1 is similar to that experienced in everyday life, in which objects which are approaching or receding undergo combined changes both in terms of their overall size and in terms of the spatial frequency content of their internal texture. The results demonstrate that the perceived size of such moving objects is biased in the direction of their motion, in much the same way as the positional misperceptions which have been found for stimuli moving in the fronto-parallel plane (Foster & Gravano, 1982; Finke, Freyd & Shyi, 1986; Hubbard & Bharucha, 1988) or undergoing rotational motion (Freyd & Finke, 1984; Kelly & Freyd, 1987; Nijhawan, 1994). The previous study of most relevance to our Experiment 1 is that of Kelly and Freyd (1987) who report an experiment in which they presented three inducing squares in succession, each one either doubling or halving in size on each presentation. A test square was then presented and subjects were required to indicate whether the test was larger or smaller than the final inducing square. Responses were biased in the direction of size change (enlargement or reduction in size) by a value of approximately 5%. Our data (Figs. 4 and 5) show biases in the same direction but of considerably larger magnitude depending upon the spatio-temporal nature of the size change.

The second type of motion which we have investigated in Experiments 2 and 3 involves a type of motion rarely, if ever, encountered in the real world, and it is probably for this very reason that strong misperceptions can occur. The motion involved an expansion or contraction of texture without the corresponding size increase which would normally be expected of such an occurrence. The result is a misperception of stimulus size in the direction in which prior visual experience tells us that size normally changes under such circumstances. Ramachandran and Anstis (1990), using random dot stimuli, found that radial motion of texture resulted in size misperceptions of around 8%. Our findings show that the size of the illusion depends strongly upon the spatio-temporal nature of the texture modulation, reaching values of up to 25%. Gregory

(1998) describes this type of visual stimulus as paradoxical. It produces a dilemma for our visual system, which must weigh up the conflicting nature of the relevant types of information (in this case expansion without a concomitant change in size) and arrive at a perceptual decision. Rather than adopt an all-or-nothing approach in which one source of information is discarded, a compromise between the two conflicting sources is reached, and it is the consequence of this compromise which we term an illusion.

There is, however, a serious problem with the concept of an homunculus continuously weighing up conflicting information to arrive at a singular percept. Illusions such as the Fraser twisted cords (Fig. 1) result in a percept which is remarkably stable and robust. It is not the case that the texture information dominates one moment and the global line orientation the next, resulting in a fluctuation in the magnitude of the illusion. So too, for our stimuli, marked misperceptions occurred yet these misperceptions were stable and consistent. To confirm this, remember that DW's *thresholds* for detecting a change in size of expanding or contracting stimuli were approximately 0.0127 log units (Fig. 7). This corresponds to a just noticeable size change of under 3%, consistent with previous Weber fractions for size and separation judgements using a variety of stimulus configurations (De Valois, Lakshminarayanan, Nygaard, Schlussel & Sladky, 1990; Levi, Jiang & Klein, 1990; Morgan, Hole & Glennerster, 1990; Whitaker & Latham, 1997). Furthermore, we measured size discrimination thresholds for our radial Gabor patches when presented statically rather than undergoing expansion or contraction. Thresholds were found to be 0.0121 log units, not significantly different to thresholds for the expanding or contracting stimuli (Fig. 7). This demonstrates that the expansion and contraction, although producing marked misperceptions in absolute size, has no effect on the precision with which size judgements can be made. The suggestion is that the illusory size changes we have documented are hard-wired—once a decision is reached regarding a stimulus attribute such as size, the decision is maintained in the absence of any marked change in stimulus configuration.

Motion of the texture characteristics of stimuli can therefore strongly influence the perceived position (Regan & Beverley, 1984; Ramachandran & Anstis, 1990; De Valois & De Valois, 1991) or size (Ramachandran & Anstis, 1990) of the whole stimulus envelope. A similar situation in the orientation domain is found in the Fraser twisted cords illusion (Fig. 1) in which visual cues provided by local texture orientation provide a global impression of slant within each line. Other illusions which possess similar local/global interactions in the orientation domain include the Café-Wall illusion and the Zöllner effect (Morgan & Moulden, 1986; Morgan & Casco, 1990). At first sight, the illusion described here appears somewhat different in that it seems to involve local/global interactions between two distinct domains, namely motion and size. However, both of these parameters share a common source in the form of position. Motion can be considered as a change in position over time, whilst an impression of size depends upon the position of the edges of a stimulus. We therefore envisage position as being the underlying primitive involved in the illusion of Experiments 2 and 3 (Westheimer, 1996), thereby complementing the well-documented illusions involving orientation.

Vincent and Regan (1997) have recently conducted experiments which also investigate the interaction between stimulus size and texture content. They measured estimated time-to-collision of square objects which were increasing in overall size. The texture content of the stimuli could be made to either increase in line with the size increase of the stimuli, or could be made to lag behind, or increase at a faster rate than the object itself. Time-to-collision estimates were significantly affected by texture manipulations, such that texture changes which lagged behind the stimulus expansion were consistently underestimated in their collision time, and vice versa. Interestingly, although the time-to-collision estimates themselves were biased, thresholds for discriminating time-to-collision remained unaffected. Similar findings had previously been reported for the interaction of texture and size in stimulating the perception of motion in depth (Beverley & Regan, 1983).

What contribution might perceived depth provide to the illusions we have found? It might be expected that our expanding stimuli provide a looming cue relative to the contracting stimuli and thereby are perceived as being closer to the observer. Perceived depth has been implicated in several of the classical size illusions such as the Müller-Lyer and Ponzo illusions. According to such explanations, perspective cues imply that different parts of these figures are positioned at different distances from the observer. Size constancy considerations lead the observer to conclude that the more perceptually distant parts of the figure are physically larger. Note, however, that such considerations are in the opposite direction to the illusion reported here. In our experiments, it was the expanding stimulus (potentially the perceptually closer stimulus) which appeared consistently larger. We therefore feel that perceived depth provides little, if any, contribution to this illusion. To emphasise, it should be noted that the magnitude of the illusion remains roughly the same under binocular viewing, a condition in which the relative (common) depth of the stimuli is likely to be judged veridically.

In our final experiment, we demonstrated that a movement after-effect, induced by adaptation to real motion, resulted in significant size misjudgements. At the level at which the size misperceptions occur, the movement after-effect and real motion are therefore indistinguishable. Had we investigated unidirectional motion within a Gabor patch, in the same way as De Valois and De Valois (1991), we can predict that inducing a movement after-effect in such stimuli would have resulted in a significant change of perceived position. A similar experiment has recently been reported by Snowden (1998) in which a vernier misalignment was produced by adaptation to horizontally moving stripes. In the orientation domain, Nishida and Johnston (1998) have recently investigated illusory orientation changes in test stimuli following adaptation to rotary motion.

In summary, we have found marked misperceptions in the perceived size of stimuli which are undergoing expansion or contraction. For objects varying jointly in the attributes of size and texture, perceived size is biased in the direction of their change, in line with biases found in a number of studies of motion extrapolation and representational momentum. The perceived size of static objects whose texture alone undergoes either real or illusory expansion or contraction is also affected, again in the direction of the texture change. We attribute this to a process in which conflicting sources of visual information are combined to form an intermediate, yet robust, percept.

Acknowledgements

PVM is supported by a Vision Research Training Fellowship from the Welcome Trust. Additional support was provided by the Visual Research Trust.

References

Beverley, K. I., & Regan, D. (1983). Texture changes versus size changes as stimuli for motion in depth. *Vision Research*, *23*, 1387–1400.

De Valois, K. K., Lakshminarayanan, V., Nygaard, R., Schlussel, S., & Sladky, J. (1990). Discrimination of relative spatial position. *Vision Research*, *30*, 1649–1660.

De Valois, R. L., & De Valois, K. K. (1991). Vernier acuity with stationary moving Gabors. *Vision Research*, *31*, 1619–1626.

Finke, R. A., Freyd, J. J., & Shyi, G. C.-W. (1986). Implied velocity and acceleration induce transformations of visual memory. *Journal of Experimental Psychology*: *General*, *115*, 175–188.

Foster, D. H., & Gravano, S. (1982). Overshoot of curvature in visual apparent motion. *Perception and Psychophysics*, *31*, 411–420.

Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology*: *Learning*, *Memory*, *and Cognition*, *10*, 126–132.

Gregory, R. L. (1998). *Eye and brain* (5th ed.). London: Oxford University.

Hubbard, T. L., & Bharucha, J. J. (1988). Judged displacement in apparent vertical and horizontal motion. *Perception and Psychophysics*, *44*, 211–221.

Kelly, M. H., & Freyd, J. J. (1987). Explorations of representational momentum. *Cognitive Psychology*, *19*, 369–401.

Levi, D. M., Jiang, B.-C., & Klein, S. A. (1990). Spatial interval discrimination with blurred lines: black and white are separate but not equal at multiple spatial scales. *Vision Research*, *30*, 1735–1750.

Morgan, M. J., & Baldassi, S. (1997). How the human visual system encodes the orientation of a texture, and why it makes mistakes. *Current Biology*, *7*, 999–1002.

Morgan, M. J., & Casco, C. (1990). Spatial filtering and spatial primitives in early vision: an explanation of the Zöllner-Judd class of geometrical illusion. *Proceedings of the Royal Society of London B*, *242*, 1–10.

Morgan, M. J., & Moulden, B. (1986). The Münsterberg figure and twisted cords. *Vision Research*, *26*, 1793–1800.

Morgan, M. J., Hole, G. J., & Glennerster, A. (1990). Biases and sensitivities in geometrical illusions. *Vision Research*, *30*, 1793–1810.

Nijhawan, R. (1994). Motion extrapolation in catching. *Nature*, *370*, 256–257.

Nishida, S., & Johnston, A. (1998). Influence of the motion after-effect on position judgment. *Perception*, *Supplement*, *27*, 50.

Ramachandran, V. S., & Anstis, S. M. (1990). Illusory displacement of equiluminous kinetic edges. *Perception*, *19*, 611–616.

Regan, D., & Beverley, K. I. (1978). Illusory motion in depth: after-effect of adaptation to changing size. *Vision Research*, *18*, 209–212.

Regan, D., & Beverley, K. I. (1984). Figure-ground segregation by motion contrast and by luminance contrast. *Journal of the Optical Society of America*, *A1*, 433–442.

Snowden, R. J. (1998). Perceived spatial position is altered by motion adaptation. *Perception*, *Supplement*, *27*, 49–50.

Vincent, A., & Regan, D. (1997). Judging the time to collision with a simulated textured object: effect of mismatching rate of expansion of object size and of texture element size. *Perception and Psychophysics*, *59*, 32–36.

Westheimer, G. (1996). Location and line orientation as distinguishable primitives in spatial vision. *Proceedings of the Royal Society of London B*, *263*, 503–508.

Whitaker, D., & Latham, K. (1997). Disentangling the role of spatial scale, separation and eccentricity in Weber's law for position. *Vision Research*, *37*, 515–524.