Perception, 2005, volume 34, pages 669 – 685

DOI:10.1068/p3444

Contrast configuration influences grouping in apparent motion†

Anna Ma-Wyatt¶, Colin W G Clifford§, Peter Wenderoth#
School of Psychology, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia;
§ Visual Perception Unit, School of Psychology, University of Sydney, Sydney, NSW 2006, Australia;
# Department of Psychology, Macquarie University, Sydney, NSW 2109, Australia; e-mail: anna@ski.org
Received 27 August 2002, in revised form 9 November 2004

Abstract. We investigated whether the same principles that influence grouping in static displays also influence grouping in apparent motion. Using the Ternus display, we found that the proportion of group motion reports was influenced by changes in contrast configuration. Subjects made judgments of completion of these same configurations in a static display. Generally, contrast configurations that induced a high proportion of group motion responses were judged as more 'complete' in static displays. Using a stereo display, we then tested whether stereo information and T-junction information were critical for this increase in group motion. Perceived grouping was consistently higher for same contrast polarity configurations than for opposite contrast polarity configurations, regardless of the presence of stereo information or explicit T-junctions. Thus, while grouping in static and moving displays showed a similar dependence on contrast configuration, motion grouping showed little dependence on stereo or T-junction information.

1 Introduction

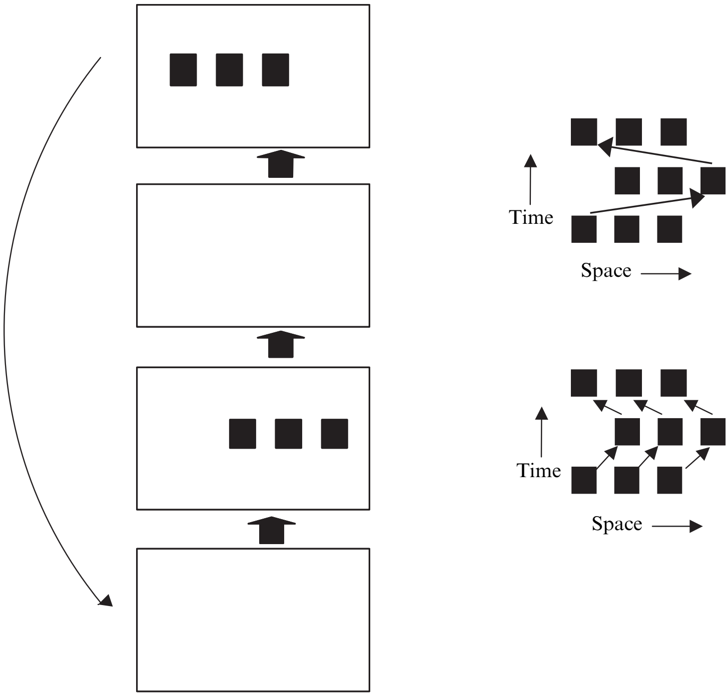
Grouping has been extensively investigated in static displays and is believed to aid in scene segmentation and figure – ground segregation (for a recent review on grouping, see Palmer et al 2003). However, the effects of grouping in motion have received comparatively little attention, possibly because it is believed that form and motion are processed separately in the visual cortex and have little influence on each other until a late stage of processing (eg Ungerleider and Mishkin 1982; DeYoe et al 1994). Recent evidence, however, indicates that form information can influence the perceived direction of motion at different levels of the visual cortex (eg Geisler 1999; Ross et al 2000; Badcock et al 2003). It is not yet clear whether the principles of grouping that are used in motion perception are the same as those for spatial vision. We investigated this question using the Ternus display.

The Ternus display is a bistable apparent-motion display in which three identical figures, separated from each other by one element width, are displaced horizontally by two element widths between frames (see figure 1a) (Pikler 1917; Ternus 1926/1938). One cycle of this stimulus typically consists of four frames, the second and fourth of which are blank—each frame separated by a blank frame. Generally, if the durations of the blank frames are sufficiently long (greater than about 70 ms) subjects report seeing the three elements move together as a group (group motion). If the durations of the blank frames are sufficiently short (less than about 50 ms), then an observer will report that the two middle elements remain stationary while the end element jumps over them. This is called element motion (see figure 1b).

If motion is thought of in terms of a space – time plot, the perception of motion in the Ternus display can be thought of in terms of competition between two types of

† Portions of this work have been presented at the Australian Experimental Psychology Conference 2001, Association for Research in Vision and Ophthalmology (ARVO) Annual Meeting 2001, and the Vision Sciences Society (VSS) Meeting 2001.

¶ Corresponding author—present address: The Smith-Kettlewell Eye Research Institute, 2318 Fillmore Street, San Francisco, CA 94115, USA; e-mail: anna@ski.org.



(a) (b)

Figure 1. (a) One cycle of the Ternus display. (b) Element motion (top) and group motion (bottom). In element motion, the end element appears to jump over the middle two to the right and back again. In group motion, the three elements appear to move as a group from left to right and back again.

grouping: one over space and one over time. If temporal grouping were stronger than spatial grouping, element motion would be reported. Strong temporal grouping would lead to strong grouping of the elements in frame one with the elements in frame three. In this case, the end element does not have a direct correspondence with an earlier frame. It would therefore be more plausibly interpreted as travelling to the end as an element. If, on the other hand, spatial grouping were stronger than temporal grouping, then group motion would be reported. Here, strong grouping within one frame could lead to the correspondence of these elements as one 'group' across frames, leading to an increase in group motion responses. The response of element or group can therefore be taken to indicate the relative strength of temporal or spatial grouping.

There is evidence in the literature that perceived apparent motion can be influenced by factors that also affect grouping and perceived surface properties in spatial vision. For example, proximity (eg Ullman 1979; Green and Odom 1986; Tse et al 1998; Gephstein and Kubovy 1999) and surface information (eg Anstis and Ramachandran 1986; He and Nakayama 1994a, 1994b) can change the path of perceived apparent motion. Shimojo and Nakayama (1990) demonstrated that the perception of motion could be constrained by amodal completion. Perceptual organisation principles that can change the perception of surfaces in static displays have also been reported to alter perceived motion in bistable apparent motion, including the Ternus display (eg Ramachandran and Anstis 1983; Kramer and Yantis 1997; Kramer and Rudd 1999; Alais and Lorenceau 2002).

These findings indicate that the perception of apparent motion can be modified by surface properties and form information, suggesting that these two types of information interact. However, little research has been conducted on how principles of grouping might constrain the interpretation of apparent motion. Here, we ask whether factors that influence the perception of grouping in static stimuli are also those that influence the perception of grouping in motion stimuli (specifically, the Ternus display).

We manipulated the presence of cues known to be crucial for the perception of surface properties. Initially, we examined the effect of contrast configuration on the perception of group motion reports. We then examined whether these same contrast configurations induced the perceived completion of the tokens in a static version of the display. In the final three experiments, we investigated whether cues thought to be important for perceived lightness in static displays (T-junctions, perceived separation of surfaces in depth) also influenced the perception of group motion in the Ternus display. If similar mechanisms affect grouping in both domains, these cues should also modify the level of group motion responses reported with the Ternus display. Our results suggest that similar types of grouping principles are used for moving displays as for static displays.

2 General methods

2.1 *Subjects*

Four experienced psychophysical observers participated in this experiment. Two of the observers were authors (AMW and CC); the other two were naive to the purposes of the experiment. All had normal or corrected-to-normal vision.

2.2 *Apparatus*

All experiments were programmed with Borland C++, and generated on a Pentium II computer with a 233 MHz processor housing a Cambridge Research Systems VSG 2/3 graphics board. Stimuli were displayed on a Sony GDM-20SE 2T5 monitor with a refresh rate of 100 Hz. The monitor was gamma corrected with Cambridge Research Systems OptiCal calibration hardware and software. Luminance values were confirmed with a Tektronix J17 spot photometer with a 1° narrow-angle luminance head (model number J1823).

A black cardboard mask with a circular aperture of diameter 180 mm was used to occlude the display outside a 760 mm viewing tube (which itself had a diameter of 280 mm). A three-button response box was used (Cambridge Research Systems, CB3).

2.3 *Stimuli*

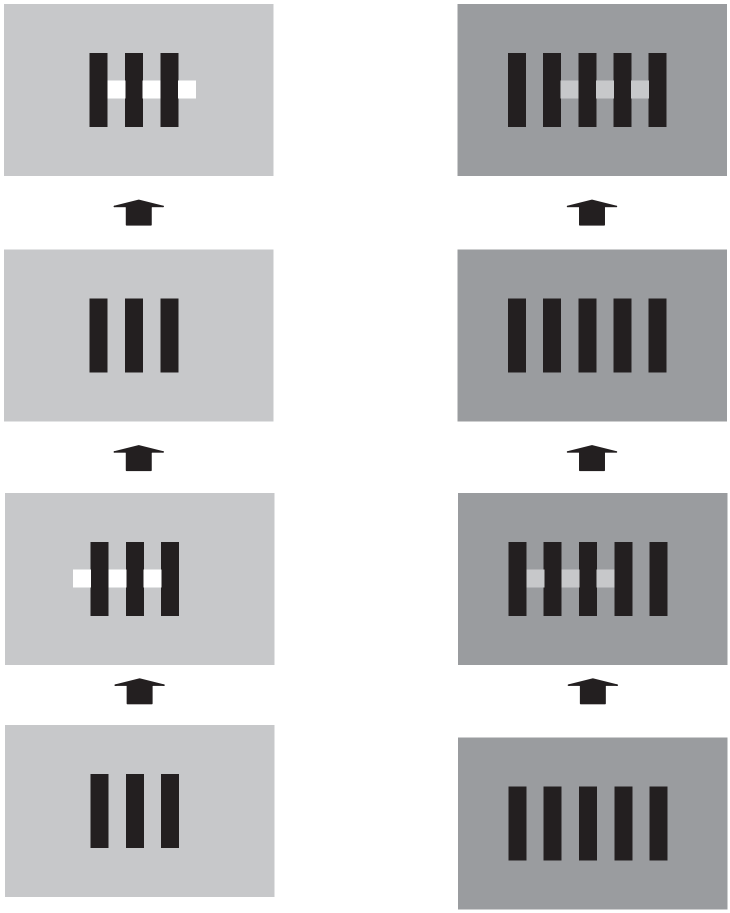
The motion tokens of the Ternus display were squares. Each side subtended 1.05 deg of visual angle. The occluders were the same width as the tokens, and their height subtended 3.75 deg of visual angle. Figure 2b contains a diagram of one cycle of the stimulus and a schematic representation of one stimulus frame from each condition.

2.4 *Procedure*

Subjects were given a brief verbal description of what the stimulus would look like. They were then shown a set of demonstration stimuli, consisting of three element motion trials [interstimulus interval (ISI) duration of 10 ms] and three group motion trials (ISI duration of 100 ms). This demonstration was repeated until the subject had correctly identified group and element motion on all trials. Each subject was then given a few hundred practice trials with an ordinary Ternus display (ie no occluders), before participating in the experiment.

In the experiment, the subjects were asked to watch the display and decide whether they had observed element or group motion. The subjects were asked to indicate their responses after the trial had ended by pressing one of two keys on a three-button response box. The programme recorded all responses in a data file.

Subject CC was not tested on ISI durations above 80 ms as he reported 100% group motion at a shorter ISI duration. Trials from each condition were randomly interleaved. As well as completing the main experiment, subjects were also tested on



(a) (b)

Figure 2. (a) A diagram of one cycle of He and Ooi's (1999) stimulus. Three vertical occluders separate the three square motion tokens. Tokens and occluders are of opposite contrast polarity relative to each other. (b) Adapted form of He and Ooi's stimulus used in the present study.

a control condition that consisted of each token contrast presented without occluders, at all ISI durations. These conditions were completed for means of comparison only, and data from these conditions were not used in any statistical analysis.

2.5 *Analysis*

Weibull functions of the following form were fitted to the distribution of each observer's raw data points in order to gain an estimate of the ISI duration for which 50% group motion responses (ISI 50) were made:

$$F(x) = N \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right],$$

where x is ISI duration, N is the number of observations made by the observer, α is an estimation of the ISI duration for which 50% group motion responses were made, and β is an estimate of the slope of the function (eg Weibull 1951). A χ^2 test was used to test if the curve fit diverged significantly from the distribution of the raw data. Once a suitable fit was made, ISI 50 was determined and used in the plotting of graphs.

Each subject's curve fit for each condition was then bootstrapped and estimates of standard error calculated (Efron and Tibshirani 1993).

3 Experiment 1

He and Ooi (1999) suggested that a decrease in ISI 50 (ie an increase in the proportion of group motion reported), observed when vertical 'occluders' were placed between motion tokens in the Ternus display, was due to the perceived completion of the tokens behind the occluders. We used an adapted form of He and Ooi's (1999) display in order to investigate the effect of contrast configuration on motion grouping. Occluders were added to either end in order to eliminate simultaneous contrast effects from the background at either end of the stimulus (see figure 2).

Increments and decrements in contrast can have differential effects on perception, even when matched in terms of Michelson contrast. There is both psychophysical and physiological evidence to suggest that increments and decrements are encoded by ON and OFF pathways (eg Shecter and Hochstein 1990; Schiller 1992; Edwards and Badcock 1994; Harris and Parker 1995). Spehar et al (1995) observed that White's illusion (White 1979) was maximal when the luminance of the test patches was between those of the inducing bars. In White's illusion, two grey patches are placed in different positions on a square-wave grating. Although the patches are of identical luminance, their perceived lightness is entirely different.

We used contrast configurations in which the tokens and the occluders were of the same contrast polarity (both increments or both decrements in contrast relative to the background), or of opposite contrast polarity. Since these conditions involve a change in the spatial relationship of different contrast values, we can refer to these changes as changes made to the spatial configuration of contrast.

3.1 *Method*

3.1.1 *Design.* A 2 (occluder luminance) $\times$ 4 (token luminance) $\times$ 10 (ISI duration) repeated-measures design was used. There were 2 levels of occluder luminance: light grey (38.6 cd m^{-2}) and dark grey (9 cd m^{-2}). The background luminance of the display was 18.6 cd m^{-2}. The Michelson contrasts of the occluders were 35% (light grey) and -49% (dark grey).

There were 4 levels of token luminance: white (52.5 cd m^{-2}), light mid-grey (26.8 cd m^{-2}), dark mid-grey (13.5 cd m^{-2}), and black (6.5 cd m^{-2}). The Michelson contrasts of these tokens were 48% (white), 18% (light mid-grey), -7% (dark mid-grey), and -85% (black). See figure 3a for one frame of each contrast configuration used.

There were 10 levels of ISI duration, running from 10 ms to 100 ms in 10 ms intervals.

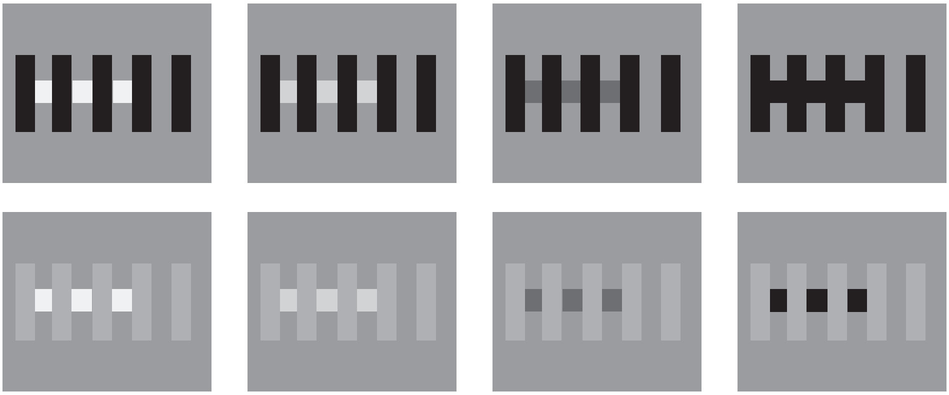
3.2 *Results*

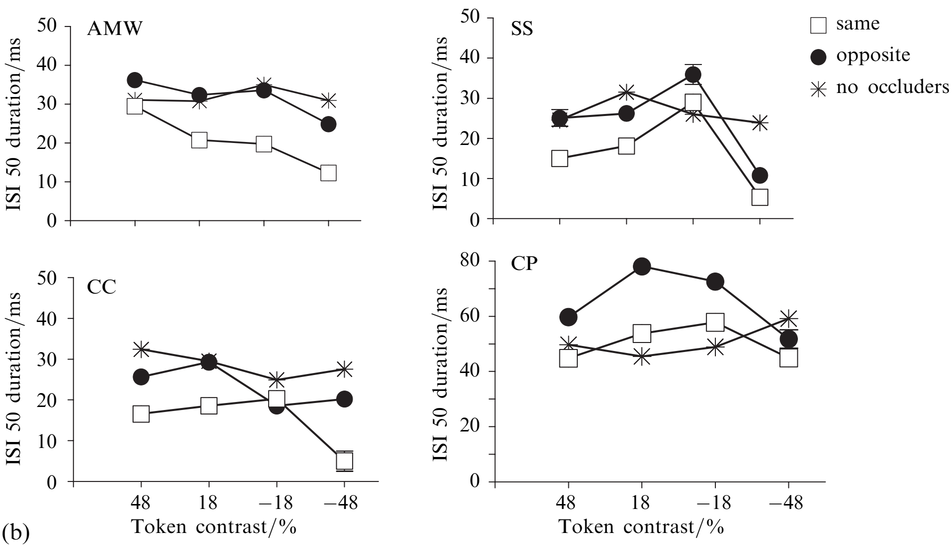
Figure 3b shows ISI 50 reported as a function of token contrast plotted with standard error bars for each observer. The bootstrap-derived standard error terms for each observer were then used to conduct *t*-tests on each observer's data. The *t*-tests were conducted in order to compare ISI 50 for the same polarity and opposite polarity conditions, for each token contrast. Since all *t*-tests were mutually independent, $\alpha = 0.05$ for each test. The results are summarised in table 1.

There was a significant difference in ISI 50 for the same polarity and opposite polarity conditions; ISI 50 was significantly shorter for same contrast polarity conditions. This was the case for all token contrasts for observers SS and AMW, and for three out of the four token contrasts for observers CC and CP.

3.3 *Discussion*

In this experiment, ISI 50 is generally shortest for conditions in which the tokens and the occluders are of the same contrast polarity. These data showed that motion grouping in the Ternus display can be influenced by the spatial configuration of contrast within the display.


(a)



(b)

Figure 3. (a) A diagram of one frame of each stimulus condition for experiment 1. In the top row, conditions with dark grey occluders; in the bottom row, conditions with light grey occluders. The token contrasts are (from left to right): white, light mid-grey, dark mid-grey, and black. Same contrast polarity conditions are those with occluders and tokens that are both increments (or decrements) in contrast and are labelled 'same'. Opposite contrast polarity conditions are those with occluders and tokens that are each an increment or a decrement in contrast polarity relative to the background and are labelled 'opposite'. (b) ISI duration for 50% group motion responses (ISI 50) as a function of occluder and token polarity for four observers, with bars representing one standard error of the mean (symbols larger than error bars in most cases). A decrease in ISI 50 is evident for same contrast polarity conditions.

The variation in responses with contrast configuration may be related to differences in the perceived surfaces of the tokens and the occluders, since it has been demonstrated that contrast configuration can influence the perception of surface properties (eg Adelson 1993; Todorović 1997). This supports earlier work showing that perceived surfaces and figures defined by subjective contours can influence the perception of apparent motion (eg Shimojo and Nakayama 1990; He and Nakayama 1994a, 1994b).

In a display with no occluders, varying the contrast of the elements has an effect on the number of group motion reports. Petersik and Pantle (1979) reported that ISI 50 decreased as contrast of the elements decreased. It can be seen in our results that there is a trend of decreasing ISI 50 with decreasing contrast of the tokens. However, there is a clear difference between conditions that have occluders of the same and opposite

Table 1. Experiment 1: Results of t-tests between same polarity and opposite polarity conditions, for each observer, at each token contrast.

Subject	Value of t			
	token contrast 48%	token contrast 18%	token contrast −7%	token contrast −85%
CC	3.56***	6.09***	0.84, ns	5.30***
SS	3.70***	3.18, $p < 0.002$	2.56, $p < 0.02$	2.42, $p < 0.002$
AMW	2.86*	6.40***	5.67***	5.28***
CP	3.81***	6.32***	3.64***	1.55, ns

$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

contrast polarity. This suggests that, although contrast of the elements does influence the perception of group motion, the decrease in ISI 50 observed in the same polarity relative to opposite polarity conditions is actually due to the change in contrast configuration, as opposed to a change in contrast of the elements alone.

4 Experiment 2

While the contrast configurations used in experiment 1 are similar to those used in several static displays in the literature, no data are available that indicate whether these particular displays do in fact increase completion and grouping judgments. We used a paradigm based on that of Spehar and Gillam (2002) in order to answer this question. Subjects were asked to judge the completion of the tokens, with each contrast configuration presented as a static display.

4.1 *Method*

4.1.1 *Subjects.* Six experienced psychophysical observers with normal or corrected-to-normal vision participated in this experiment. Two of these observers were authors (AMW and CC); the others were naive to the purposes of the experiment.

4.1.2 *Stimuli.* Stimuli were identical to those presented in the first frame of the cycle of stimuli in experiment 1.

4.1.3 *Procedure.* A two-alternative forced-choice paired-comparison procedure was employed. Two contrast configurations were presented to the subject—one on the left-hand side of the screen and one on the right. Each contrast configuration was compared with every other contrast configuration. Subjects were asked to judge whether the tokens on the left-hand side of the screen or those on the right-hand side of the screen looked most complete, and to indicate this response by pressing a button on a three-button response box.

4.2 *Results*

Subjects completed at least thirty judgments of each paired comparison. These raw data were collated as a proportion of 'most complete' responses (figure 4). Conditions in which the tokens and the occluders were of the same contrast polarity were generally judged as more complete, compared to conditions in which the tokens and occluders were of opposite contrast polarity. This was the case for five out of six observers, with the exception of subject SR, who showed the opposite pattern of results. It is possible that SR was using a different criterion for completion than other subjects.

4.3 *Discussion*

The results of experiment 2 show that in static displays, conditions in which the tokens and occluders are of the same contrast polarity are judged most complete. The trend for token contrast is similar but not identical between the two experiments. The token contrast

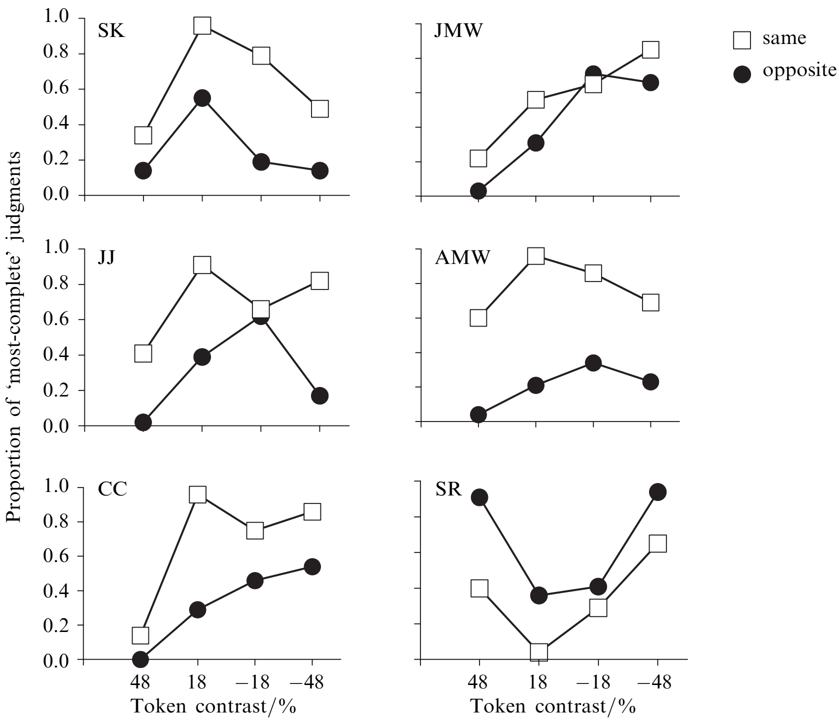


Figure 4. Proportion of 'most complete' responses for six observers, for judgment of static displays. Generally, same contrast polarity displays were judged as more complete than opposite contrast polarity displays.

that leads to the lowest ISI 50 is not necessarily the token contrast that gives the highest proportion of complete responses for the static judgment. However, there is a strong trend evident for both static and moving displays: same contrast polarity occluders and tokens promote completion and grouping of the tokens into one long token. These findings suggest that a similar mechanism may underlie the perception of grouping in both moving and static displays—one which is sensitive to contrast polarity but not the value of token luminance.

In the next three experiments, we investigated whether cues known to be influential for grouping and perceived surface properties in static displays were also important for grouping in the Ternus display.

5 Experiment 3: Perceived depth of tokens relative to occluders

The results of experiment 2 suggest that completion cues were important for the increase in grouping observed in experiment 1. However, completion information can also provide information about perceived depth and surface scission. Gilchrist (1977) argued that changes in perceived lightness with different-contrast configurations were due to the interpretation of these contrast configurations as cues to depth.

If Gilchrist's account is correct, then providing real and consistent depth information should strengthen the grouping of different portions of the display at different depths. ISI 50 should now be similar across conditions, since the depth information will provide consistent information about the perceived separation in depth of the elements and the occluders across all conditions. In the present experiment, depth cues are given by both monocular occlusion and disparity information. The coplanar condition was included as a baseline measure, to ensure that presenting the tokens and occluders in disparity did not lead to any reduction of the effects of changing contrast configuration.

It should also be noted that, in the following three experiments, equal increments and decrements in Michelson contrast were used. There is evidence in both the spatial-vision and apparent-motion literature that indicates that increments and decrements in contrast are treated differently by the visual system—equivalent steps in Michelson contrast in increments and decrements do not lead to comparable changes in behaviour (eg Shecter and Hochstein 1990; Spehar and Zaidi 1997). For the purposes of the following experiments, we standardised the increments and decrements in Michelson contrast. In all experiments, there was a significant effect of contrast configuration rather than token contrast.

5.1 *Method*

5.1.1 *Design.* A 3 (disparity) × 2 (occluder contrast) × 4 (token contrast) × 7 (ISI duration) repeated-measures design was used for this experiment.

The 3 levels of disparity were: in front of (fore), behind (aft), and the same disparity (coplanar) as the motion tokens. The disparity of the motion tokens remained constant at a crossed disparity of 17.4 min of arc. In the fore condition, the occluders had a disparity of 0. For the aft condition, the occluders had a crossed disparity of 34.8 min of arc.

The luminance of the background was 18.6 cd m^{-2}. There were 2 levels to the factor of occluder luminance: light grey (38.6 cd m^{-2}) and dark grey (9 cd m^{-2}), corresponding to contrasts of +35% and −35%, respectively.

There were 4 levels to the factor of token luminance: white (52.5 cd m^{-2}), light mid-grey (26.8 cd m^{-2}), dark mid-grey (13.5 cd m^{-2}), and black (6.5 cd m^{-2}). The contrasts of the tokens were as follows: white (+48%), light mid-grey (+18%), dark mid-grey (−18%), and black (−48%).

There were 7 levels for the factor of ISI duration: 10 – 70 ms in 10 ms increments.

5.1.2 *Subjects.* Four experienced psychophysical observers participated in this experiment, all with normal vision. Two of the observers were authors (AMW and CC); the other two were naive to the purposes of the experiment. All subjects were tested for stereo vision with the Randot stereo test (Stereo Optical Co., Inc.).

5.1.3 *Apparatus.* All stimuli were viewed through a haploscope. The apparatus was otherwise identical to that described in experiment 1.

5.1.4 *Stimuli.* The stimuli were of the same configuration as that shown in figure 2. The contrast configurations used were identical to those used in experiment 1 (see figure 3 for a diagram of one frame of each contrast configuration). Figure 5 contains diagrams of a binocular view and of monocular views of the fore condition.

5.1.5 *Procedure.* The procedure was identical to that described in experiment 1, with the following additions. Subjects viewed the display using a haploscope. Each subject completed a short calibration task before each run to ascertain the correct on-screen separation at which to present the stimuli such that they would be able to fuse the two images. In the calibration task, subjects were presented dichoptically with an outline of a circle and a square presented at a distance from the centre of the display. The observer's task was to adjust the position of the circle such that it was lying within the square with the sides of the square tangent to the circle. These positions were then used throughout the experiment. A circle distant from the stimulus was used as a fusion lock and was present for the duration of the stimulus.

Subjects were also tested separately on a control condition. This condition consisted of the tokens only (ie without occluders) presented at a crossed disparity of 17.4 min of arc. These data are presented in the plots for means of comparison only—they were not used in the statistical analysis of the data.

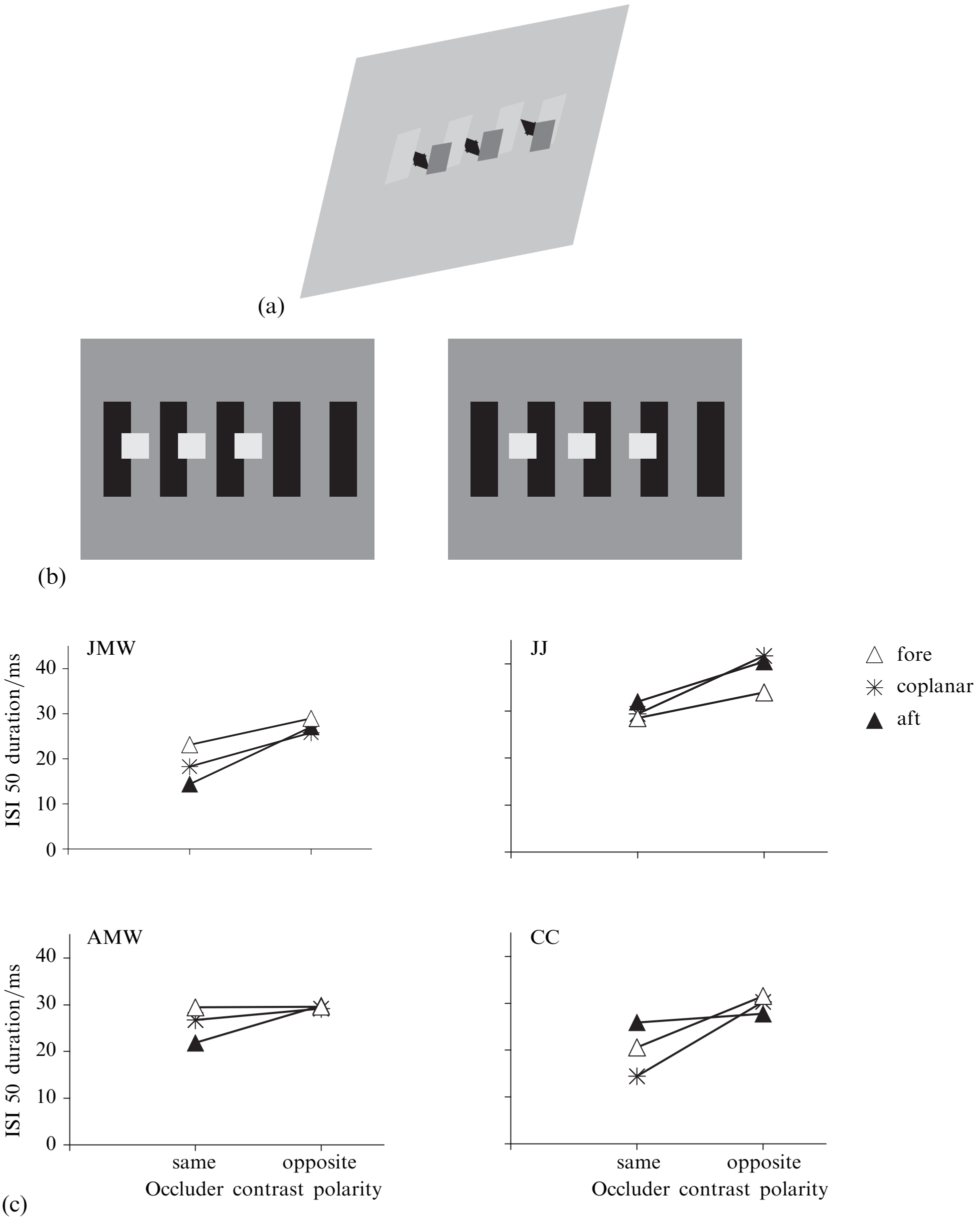


Figure 5. (a) Binocular view of stereo stimuli used in experiment 3. Tokens in crossed disparity, in front of occluders (fore condition). (b) Monocular views of the fore condition. (c) ISI durations for 50% group motion reports (ISI 50), averaged across observers, as a function of occluder polarity and token contrast, for each depth condition. There was a decrease in ISI 50 for same contrast polarity conditions, and no significant effect of depth.

5.2 *Results*

The data were processed in the same manner as described for experiment 1. Figure 5c shows ISI 50 for group motion responses, averaged across observers and plotted as a function of occluder polarity and token contrast. A multivariate analysis of variance of the repeated-measures data was conducted to examine the overall effect of contrast polarity of the occluders, token contrast, and depth of the tokens relative to the occluders. The results of this analysis showed that there was a significant main effect for occluder polarity ($F_{1,72} = 34.64$, $p < 0.0001$) and for token contrast ($F_{3,72} = 10.22$, $p < 0.0001$).

In conditions in which the occluders and tokens were of the same contrast polarity, there was a significantly shorter ISI 50 compared to conditions in which the tokens and occluders were of opposite contrast polarity. Generally, there was a monotonic decrease in ISI 50 with increasing token contrast. There was no significant effect of depth and there were no other significant effects.

5.3 *Discussion*

While the results showed that presenting the tokens and occluders in crossed and uncrossed disparity can alter motion grouping to some extent, perceived depth was not a strong enough cue to obliterate all differences in contrast configuration. From this we conclude that the effect of contrast configuration is not solely to promote a perceived separation of the surfaces in depth. Gilchrist (1977) has argued that certain configurations mimic situations in the real environment in which figures are separated in depth. Our results suggest that, while same contrast polarity does promote completion and grouping, it does not do so in a manner similar to a separation in perceived depth. Other cues must be critical in explaining this effect. Zaidi et al (1997) have demonstrated that Gilchrist's (1977) argument does not hold for all contrast configurations. They found that T-junctions, not depth relationships like perceived coplanarity, were critical for several lightness illusions induced by contrast configuration.

6 Experiment 4: Role of T-junctions

T-junctions can be crucial for the perception of surface properties (eg Spehar and Zaidi 1997; Todorović 1997; Zaidi et al 1997), and it has been suggested that T-junctions act to inhibit induced contrast. Spehar and coworkers have proposed that a functional account for T-junctions might be that they signal occlusion in natural environments. Changes in perceived contrast observed in displays like White's illusion might be mediated by mid-level processing (Spehar and Zaidi 1997; Zaidi et al 1997). Mid-level processing could take into account T-junction and X-junction information in order to constrain induced contrast effects. Occlusion information can also have a significant effect on perceived direction of motion within an aperture (eg Wallach 1935/1996; Nakayama and Silverman 1988a, 1988b; van der Smagt and Stoner 2002). Nakayama and Silverman conducted a series of elegant experiments in which they highlighted the importance of occlusion information for the computation of motion direction from ambiguous motion signals within an aperture.

He and Ooi (1999) argued that, in their experiments, subjects may have amodally completed the tokens behind the occluders into one long bar. This in turn increased grouping since the tokens were grouped together as a bar. Amodal completion has been shown to contribute to perceptual grouping in static displays (eg Palmer et al 1996). In order for amodal completion to occur in the display that has been used thus far, T-junctions needed to be present. Removing T-junctions by introducing a gap between the tokens and the occluders should weaken amodal completion and therefore reduce spatial grouping. There should also be virtually no difference between the different contrast conditions. Without T-junctions, and without the effect of adjacent areas of a different contrast, the occluders should have a greatly reduced effect on the perception of motion of the tokens.

6.1 *Method*

6.1.1 *Subjects.* Three experienced psychophysical observers participated in this experiment. Two were authors (AMW and CC); the other was naive to the purposes of the experiment. All subjects had normal vision and were screened for stereo vision with the Randot stereo test.

6.1.2 *Stimuli.* The stimuli were of the same configuration as that used in experiment 1, but the motion tokens were smaller (31.5 min of arc), while the occluders were of the same size as previously reported. The size of the tokens meant that there was a gap between both sides of each token and the occluders, in both the left-eye and right-eye views. Figure 6a shows a diagram of one frame of the stimulus (binocular view).

6.1.3 *Procedure.* The procedure was the same as that outlined in experiment 3.

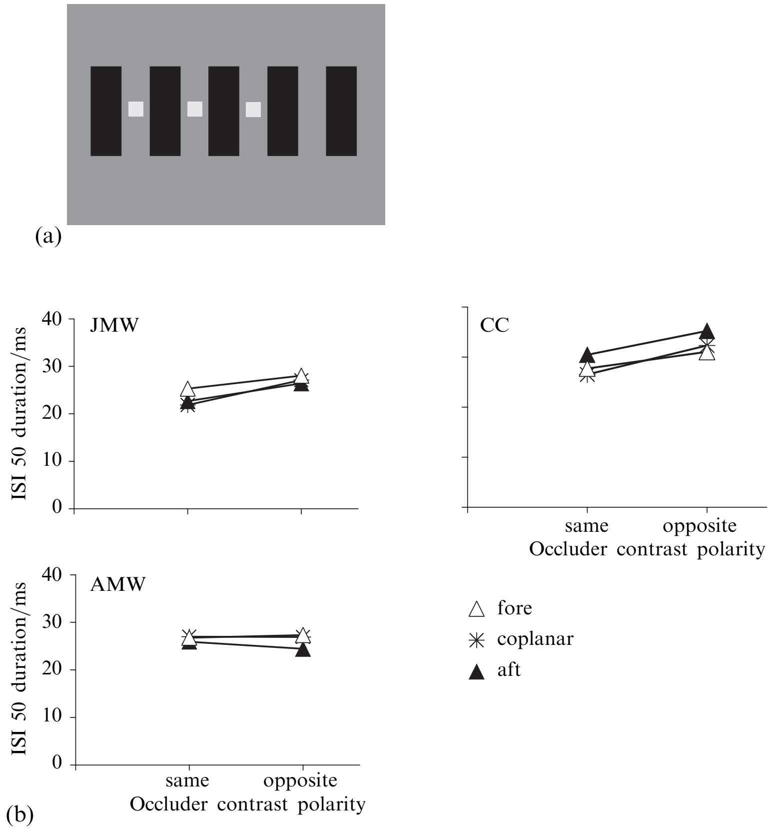


Figure 6. (a) Binocular view of one frame of no T-junction condition for experiment 4. (b) ISI durations for 50% group motion reports (ISI 50), averaged across observers, as a function of occluder polarity and token contrast, for each depth condition. There was a decrease in ISI 50 for same contrast polarity conditions, and no significant effect of depth.

6.2 *Results*

Figure 6b shows ISI 50, averaged across observers, plotted as a function of token contrast, for each contrast polarity condition, at each depth. There was a reduction in ISI 50 for same contrast polarity versus opposite contrast polarity conditions.

There was a general trend of shorter ISI 50 in conditions in which the occluders and tokens were of the same contrast polarity, compared to conditions in which tokens and occluders were of opposite contrast polarity. A general monotonic decrease in ISI 50 with increasing token contrast was also evident. A multivariate analysis of variance of the repeated-measures data showed that there was a significant main effect for occluder polarity ($F_{1,48} = 9.364$, $p < 0.005$) and for token contrast ($F_{3,48} = 19.177$, $p < 0.0001$). There was also a significant interaction between occluder polarity and token contrast ($F_{3,48} = 8.774$, $p < 0.0001$). There were no other significant effects.

6.3 *Discussion*

Without T-junctions, there was still a decrease in ISI 50 for conditions in which the tokens and occluders were of same contrast polarity, demonstrating that T-junctions are not crucial for this effect. The magnitude of the effect is smaller than that observed in experiment 1, suggesting that the absence of T-junctions may have reduced the difference between amodal and modal completion.

A reviewer asked us whether size alone might account for the change in responses seen in experiment 4, as opposed to the eradication of T-junctions. With reduced size of the elements, there is also an increase in the distance between elements. Recent work suggests that the size of individual elements can change perceived shape and the strength of grouping (Pelli 1999; Ma-Wyatt 2002). Ma-Wyatt (2002) showed that if all elements fell within 0.5 deg of visual angle, only group motion was reported. Above this size, a typical Ternus function was observed. Our present stimulus was 1.25 deg in total, well above that reported by Ma-Wyatt.

Even at the reduced element size present in this experiment, we still observed a significant albeit reduced difference between the same polarity and opposite polarity conditions. If the reduced size of the elements did reduce the strength of grouping in the display, it still cannot account for the significant difference between same polarity and opposite polarity conditions.

7 Experiment 5

Monocular occlusion information was present in the initial depth experiment, but not in the no T-junction conditions. The present experiment was designed to directly test the involvement of monocular occlusion as a cue that may be promoting grouping. If the previous result of a decrease in ISI 50 for same contrast polarity conditions was due to T-junction information consistent with amodal completion, then one could predict that the reduction in grouping would be the greatest for the fore condition, while the aft condition would reduce grouping to a lesser degree. The fore condition gave the clearest information that the tokens were discrete units, since one could see the whole token. In this condition, the T-junction information was consistent with the tokens being in front of the occluders, on a different plane. T-junction information in the aft condition was consistent with amodal completion of the tokens into one long token.

7.1 *Method*

7.1.1 *Design.* This experiment had a 2 (monocular occlusion) $\times$ 2 (occluder luminance) $\times$ 4 (token luminance) $\times$ 7 (ISI duration) repeated-measures design. There were 2 levels to the factor of monocular occlusion—tokens either appeared in front of (fore), or behind the occluders (aft). The disparity of the display (motion tokens and occluders) remained constant at 17.4 min of arc. The levels of all other factors were identical to those reported in experiment 3.

7.1.2 *Subjects.* Four experienced psychophysical observers participated in this experiment. Two were authors (AMW and CC); the others were naive to the purposes of the experiment. All had normal stereo vision, as tested with a Randot stereo test.

7.1.3 *Stimuli.* The stimuli were of the same size and same configuration as that used in experiment 3. The only difference was that in this experiment there was a shift in the position of the tokens relative to the occluders. This meant that there was a space between the occluders and the tokens, such that there was no T-junction information on the side with this space. In the fore condition, the tokens overlapped the occluders ('occluding' the occluders). In the aft condition, the occluders occluded the tokens. A diagram of one frame of the stimulus for each of the fore and aft conditions is presented in figure 7a. Each frame shows a binocular view of the stimulus.

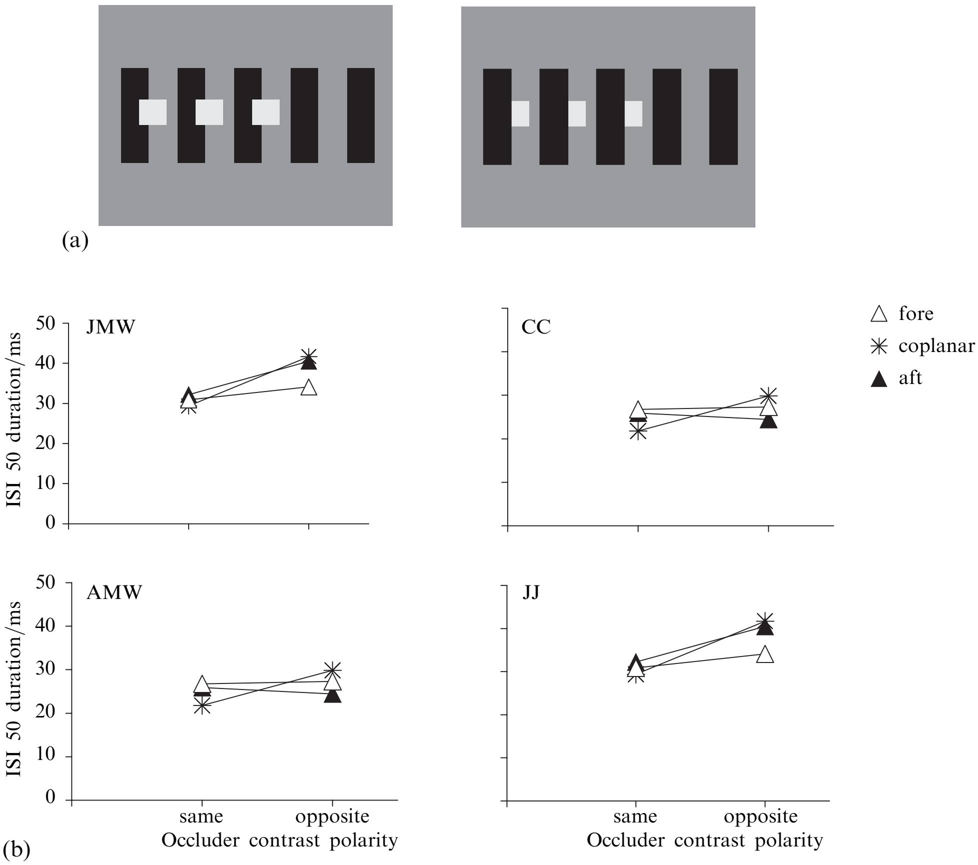


Figure 7. (a) Binocular view of stimuli for experiment 5. On the left, fore condition (tokens occlude the occluders). On the right, aft condition (tokens occluded by occluders). (b) ISI durations for 50% group motion reports (ISI 50), averaged across observers, as a function of occluder polarity and occlusion condition. There was a decrease in ISI 50 for same contrast polarity conditions, and no significant effect of occlusion condition. Coplanar data are reproduced here from experiment 3.

7.2 *Results*

A multivariate analysis of variance for the repeated-measures data showed that there was a significant main effect for occluder polarity ($F_{1,72} = 23.425$, $p < 0.0001$) and for token contrast ($F_{3,72} = 7.216$, $p < 0.001$). There was a trend of shorter ISI 50s for same polarity occluders as opposed to opposite polarity occluders, across all conditions. There was also a general trend of increased group motion responses with increasing token contrast. No other effects were significant. Figure 7b shows ISI 50, averaged across observers, plotted as a function of occluder polarity and token contrast for all depth conditions.

When there was only monocular occlusion information present, there was a similar ISI 50 for both the fore and aft conditions. There was a reduction in ISI 50 between the same polarity and opposite polarity conditions for three of the four observers. ISI 50 was shortest for the coplanar same polarity condition, as in experiments 1 and 3.

7.3 *Discussion*

With a display that contains only monocular occlusion cues, there was still an effect of contrast polarity. ISI 50 is decreased in conditions where the occluders and the tokens are of the same contrast polarity compared to conditions in which the occluders and tokens are of opposite contrast polarity, in both the fore and aft conditions.

Interestingly, the number of group motion responses is similar for both the fore and aft conditions. This result suggested that it was T-junction information in general, not only T-junction information consistent with amodal completion, which led to a decrease in ISI 50.

8 General discussion

Experiment 1 demonstrated that a change in contrast configuration of a Ternus display containing occluders changes ISI 50, resulting in an increase in group motion responses. ISI 50 was significantly decreased in conditions in which the tokens and occluders were of the same contrast polarity. Experiment 2 showed that, for judgments of completion within one frame of each condition, same contrast polarity conditions were judged as more complete than opposite contrast polarity conditions, consistent with the notion that similar cues are used in both domains. In experiment 3, binocular disparity cues were used to manipulate the perceived depth of the tokens relative to the occluders. This manipulation led to a decrease in ISI 50 to only a small extent, suggesting that the effects of contrast configuration were not limited to a perceived separation in depth of the tokens and occluders.

Experiment 4 demonstrated that when T-junctions were removed there was no significant effect of binocular disparity alone. There was still a significant difference between ISI 50 for same polarity and opposite polarity tokens and occluders, suggesting that the changes in motion grouping observed with changes in contrast configuration were not due to the presence of T-junctions alone. Experiment 5 showed that when monocular occlusion cues alone were present, the fore and aft conditions yielded very similar response functions. There are different types of T-junction information in the two conditions. However, both had a similar level of grouping, which in turn was close to, though less than, that of the coplanar conditions, suggesting that there was no differential effect of the type of T-junctions present.

Altogether, the results demonstrate that contrast configuration can significantly influence motion grouping in the Ternus display. We consistently found an increase in group motion reports with same contrast polarity configurations, relative to opposite contrast polarity configurations. In the absence of T-junctions, the difference in group motion reports between same contrast polarity and opposite contrast polarity conditions was still significant although somewhat reduced. We conclude that contrast configurations significantly influence the perception of motion grouping, but unlike displays used in spatial vision, explicit T-junctions do not seem to be crucial for this effect.

These results are consistent with the findings of He and Ooi (1999) in that they demonstrate that perceptual organisation principles can influence the perception of motion in an apparent-motion display. Alais and Lorenceau (2002) investigated association fields between collinear elements using group motion reports in the Ternus display as an index of the strength of the association field. Gephstein and Kubovy (1998) showed that proximity in both time and space could influence the perceived direction of motion in an apparent-motion display. The work presented here extends these earlier findings. Our results demonstrated that changes in contrast configuration that influence surface properties also influence motion grouping, suggesting that a common mechanism may process grouping in both static and motion displays.

In spatial vision, mid-level processes have been proposed to mediate the effects of changing contrast configuration (eg Anderson 1997). The neurophysiological substrate of the processing of mid-level information could be as early as primary visual cortex (V1). Cells in V1 are reported to be tuned for occlusion (Sugita 1999) and can be influenced by luminance configuration extending 10° to 20° beyond the receptive field of the neuron (MacEvoy et al 1998). Although representation of extra-receptive field interactions and occlusion has been observed as early as V1, it is not clear whether motion grouping is mediated in V1 or at a later stage of cortical processing.

Geisler (1999) and Ross et al (2000) have demonstrated that form information can be used to determine motion direction at both early and late stages of the visual cortex. Recent evidence suggests that the perception of motion in the Ternus display is primarily mediated by a feature-tracking mechanism (eg Scott-Samuel and Hess 2001). Our results are consistent with a mechanism in which a high-level motion detector is constrained by grouping principles.

The Ternus display offers a way to investigate grouping within a paradigm in which motion information is not influenced only by proximity. Changes in contrast configurations that lead to an increase in completion judgments in static displays can also increase motion grouping in the Ternus display. A common mechanism may process grouping in both cases, supporting the argument that form and motion information interact in the processing of motion information (eg Ross et al 2000; Badcock et al 2003).

Acknowledgments. Thank you to JMW, JJ, and CP for patient observation, and Branka Spehar, John Ross, David Badcock, and David Burr for helpful discussions.

References

Adelson E H, 1993 "Perceptual organization and the judgment of brightness" *Science* **262** 2042 – 2044

Alais D, Lorenceau J, 2002 "Perceptual grouping in the Ternus display: evidence for an 'association field' in apparent motion" *Vision Research* **42** 1005 – 1016

Anderson B L, 1997 "A theory of illusory lightness and transparency in monocular and binocular images: the role of contour junctions" *Perception* **26** 419 – 453

Anstis S, Ramachandran V, 1986 "Entrained path deflection in apparent motion" *Vision Research* **26** 1731 – 1739

Badcock D R, McKendrick A M, Ma-Wyatt A, 2003 "Pattern cues can determine perceived direction in simple moving stimuli" *Vision Research* **43** 2291 – 2301

Braddick O J, Adlard A, 1978 "Apparent motion and the motion detector", in *Visual Psychophysics and Psychology* Eds J C Armington, J Krauskopf, B R Wooten (San Diego, CA: Academic Press) pp 417 – 426

Carney T, 1997 "Evidence for an early motion system which integrates information from the two eyes" *Vision Research* **37** 2361 – 2368

Cohen J, 1991 *Statistical Power Analysis for the Behavioral Sciences* (New York: Lawrence Erlbaum Associates)

DeYoe E A, Fellerman D J, Van Essen D C, McClendon E, 1994 "Multiple processing streams in occipitotemporal visual cortex" *Nature* **371** 151 – 154

Edwards M, Badcock D R, 1994 "Global motion perception: interaction between ON and OFF pathways" *Vision Research* **34** 2849 – 2858

Efron B, Tibshirani R J, 1993 *An Introduction to the Bootstrap* (London: Chapman and Hall)

Geisler W S, 1999 "Motion streaks provide a spatial code for motion direction" *Nature* **400** 65 – 69

Gephstein S, Kubovy M, 1999 "The emergence of visual objects in space – time" *Proceedings of the National Academy of Sciences of the USA* **97** 8186 – 8191

Gilchrist A L, 1977 "Perceived lightness depends on perceived spatial arrangement" *Science* **195** 185 – 187

Green M, Odom V J, 1986 "Correspondence matching in apparent motion—evidence for 3-dimensional representation" *Science* **233** 1427 – 1429

Harris J, Parker A, 1995 "Independent neural mechanisms for bright and dark information in binocular stereopsis" *Nature* **374** 808 – 810

He Z J, Nakayama K, 1994a "Perceived surface shape not features determines correspondence strength in apparent motion" *Vision Research* **34** 2125 – 2135

He Z J, Nakayama K, 1994b "Apparent motion determined by surface layout not by disparity or three-dimensional distance" *Nature* **367** 173 – 175

He Z J, Ooi T L, 1999 "Perceptual organization of apparent motion in the Ternus display" *Perception* **28** 877 – 892

Kramer P, Rudd M, 1999 "Visible persistence and form correspondence in Ternus apparent motion" *Perception & Psychophysics* **61** 952 – 962

Kramer P, Yantis S, 1997 "Perceptual grouping in space and time: Evidence from the Ternus display" *Perception & Psychophysics* **59** 87 – 99
MacEvoy S P, Kim W, Paradiso M A, 1998 "Integration of surface information in primary visual cortex" *Nature Neuroscience* **1** 616 – 620
Ma-Wyatt A, 2002 "Size affects grouping in apparent motion" *Perception* **31** Supplement, 83a
Nakayama K, Silverman G H, 1998a "The aperture problem—I. Perception of nonrigidity and motion direction in translating sinusoidal lines" *Vision Research* **28** 739 – 746
Nakayama K, Silverman G H, 1988b "The aperture problem—II. Spatial integration of velocity information along contours" *Vision Research* **28** 747 – 753
Palmer S, Brooks J L, Nelson R, 2003 "When does grouping happen?" *Acta Psychologica* **114** 311 – 330
Palmer S, Neff J, Beck D, 1996 "Late influences on perceptual grouping: amodal completion" *Psychonomic Bulletin and Review* **3** 75 – 80
Patterson R, Hart P, Nowak D, 1991 "The cyclopean Ternus display and the perception of element versus group movement" *Vision Research* **31** 2085 – 2092
Pelli D G, 1999 "Close encounters—an artist shows that size affects shape" *Science* **285** 844 – 846
Petersik J T, Pantle A, 1979 "Factors controlling the competing sensations produced by a bistable stroboscopic motion display" *Vision Research* **19** 143 – 154
Pikler J, 1917 *Sinnesphysiologische Untersuchungen* (Leipzig: Barth)
Ramachandran V, 1988 "Perceiving shape from shading", in *The Perceptual World* Ed. I Rock (New York: W H Freeman) pp 127 – 138
Ramachandran V S, Anstis S M, 1983 "Perceptual organization in moving patterns" *Nature* **304** 529 – 531
Ross J, Badcock D R, Hayes A, 2000 "Coherent global motion in the absence of coherent velocity signals" *Current Biology* **10** 679 – 682
Schiller P H, 1992 "The ON and OFF channels of the visual system" *Trends in Neurosciences* **15** 86 – 92
Scott-Samuel N E, Hess R F, 2001 "What does the Ternus display tell us about motion perception in human vision?" *Perception* **30** 1179 – 1188
Shecter S, Hochstein S, 1990 "ON and OFF pathway contributions to apparent motion perception" *Vision Research* **30** 1189 – 1204
Shimojo S, Nakayama K, 1990 "Amodal representation of occluded surfaces: role of invisible stimuli in apparent motion correspondence" *Perception* **19** 285 – 299
Smagt van der M J, Stoner G R, 2002 "Context and the motion aftereffect: Occlusion cues in the test pattern alter perceived direction" *Perception* **31** 39 – 50
Spehar S, Gilchrist A, Arend L, 1995 "The critical role of relative luminance relations in White's effect and grating induction" *Vision Research* **35** 2603 – 2614
Spehar B, Gillam B, 2002 "Modal completion in the Poggendorff illusion: Support for the depth processing theory" *Psychological Science* **13** 306 – 312
Spehar B, Zaidi Q, 1997 "New configurational effects on perceived contrast and brightness: second-order White's effects" *Perception* **26** 409 – 417
Sugita Y, 1999 "Grouping of image fragments in primary visual cortex" *Nature* **401** 269 – 272
Ternus J, 1926/1938 "The problem of phenomenal identity", English translation in *A Source Book of Gestalt Psychology* Ed. W D Ellis (1938, London: Routledge and Kegan Paul)
Todorović D, 1997 "Lightness and junctions" *Perception* **26** 379 – 394
Tse P, Cavanagh P, Nakayama K, 1998 "The role of parsing in high-level motion processing", in *High-Level Motion Processing* Ed. T Watanabe (Cambridge, MA: MIT Press) pp 249 – 266
Ullman S, 1979 *The Interpretation of Visual Motion* (Cambridge, MA: MIT Press)
Ungerleider L G, Mishkin M, 1982 "Two cortical visual systems", in *Analysis of Visual Behavior* Eds D J Ingle, M A Goodale, R J W Mansfield (London: MIT Press) pp 549 – 587
Wallach H, 1935/1996 "Über visuell wahrgenommene Bewegungsrichtung" *Psychologische Forschung* **20** 325 – 380 [English translation with an introduction by S Wuerger, R Shapley, N Rubin "'On the visually perceived direction of motion' by Hans Wallach: 60 years later" *Perception* 1996 **25** 1317 – 1367]
Weibull W, 1951 "A statistical distribution function of wide applicability" *Journal of Applied Mechanics* **18** 293 – 297
White M, 1979 "A new effect of pattern on perceived lightness" *Perception* **8** 413 – 416
Zaidi Q, Spehar B, Shy M, 1997 "Induced effects of backgrounds and foregrounds in three-dimensional configurations: the role of T-junctions" *Perception* **26** 395 – 408

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 34 2005

www.perceptionweb.com