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The shape and size of crowding for moving targets

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Abstract

Our ability to identify alphanumeric characters can be impaired by the presence of nearby features, especially when the target is presented in the peripheral visual field, a phenomenon is known as *crowding*. We measured the effects of motion on acuity and on the spatial extent of crowding. In line with many previous studies, acuity decreased and crowding increased with eccentricity. Acuity also decreased for moving targets, but the absolute size of crowding zones remained relatively invariant of speed at each eccentricity. The two-dimensional shape of crowding zones was measured with a single flanking element on each side of the target. Crowding zones were elongated radially about central vision, relative to tangential zones, and were also asymmetrical: a more peripheral flanking element crowded more effectively than a more foveal one; and a flanking element that moved ahead of the target crowded more effectively than one that trailed behind it. These results reveal asymmetrical space-time dependent regions of visual integration that are radially organised about central vision.

Keywords: Crowding; Motion; Trajectory; Acuity

1. Introduction

It is well established that an observer's ability to identify an alphanumeric character is reduced when it is surrounded by other optotypes (Bouma, 1970; Townsend, Taylor, & Brown, 1971) or contours (Flom, Weymouth, & Kahneman, 1963). This effect is known as *crowding*, or *local contour interaction*. The region around the target associated with reduced identification under crowded viewing conditions is known as the *spatial interference zone* or *crowding zone*. The spatial extent of crowding increases in peripheral vision even when image size or contrast is increased to equate visibility across the visual field (Bouma, 1970; Chung, Levi & Legge, 2001; Hess, Dakin, Kapoor, & Tewfik, 2000; Jacobs, 1979; Latham & Whitaker, 1996b; Loomis, 1978; Strasburger, Harvey, & Rentschler, 1991; Toet & Levi, 1992; Wolford & Chambers, 1984).

The perception of spatial detail is thought to be limited by the resolution acuity of at least two stages of visual processing. At the first stage, optical (linear) filtering and visual quasi-linear filtering factors (e.g. spatial frequency channels) limit the spatial structure that can be encoded. At later stages resolution is constrained by non-linear visual processes of integration and attention that group and segment the features coded by the first stage and limit features that can be individuated. Explanations of crowding have been based on limitations at either or both of these stages.

Visual acuity can be reduced under crowded conditions by interactions in the physics of the target and flanking stimuli in the retinal image, such as the point spread function (Liu & Arditi, 2000) or masking by the spatial frequency components they share (Bondarko & Danilova, 1997; Hess, Dakin, & Kapoor, 2000). However, crowding also occurs between target and flank stimuli that are presented to opposite eyes (Flom et al., 1963; Tripathy & Levi, 1999), implicating a cortical locus for at least some component of spatial interference. Crowding effects are maximal when the spatial (Kooi, Toet, Tripathy, & Levi, 1994b; Nazir, 1992), spatial frequency (Andreissen & Bouma, 1976; Chung, Levi & Legge, 2001; Hess, Dakin, & Kapoor, 2000; Kooi, Toet, Tripathy, & Levi, 1994a) or orientation (Levi, Klein, & Hariharan, 2002) structure of the target and flanking stimuli are similar. Thus spatial interference is greater among channels that are similarly tuned for contrast polarity, spatial frequency and orientation

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than across differently tuned channels. Tuning properties for foveal crowding are similar to those reported for masking (Polat & Sagi, 1993; Wilson, McFarlane, & Phillips, 1983; Zenger & Sagi, 1996) and indeed some authors have presented evidence that foveal crowding can be considered a masking phenomenon (Chung, Levi & Legge, 2001; Levi, Hariharan, & Klein, 2002).

While such masking among similarly tuned channels might account for crowding in foveal vision, differences between crowding effects in foveal and peripheral visual field are not consistent with this explanation and require a different model. In the periphery, crowding effects are equal for targets and flankers that are of either the same or opposite contrast polarity (Hess et al., 2000). The extent of spatial interference does not scale with the spatial frequency of the target as it does in fovea (Chung, Levi & Legge, 2001; Levi, Hariharan et al., 2002) or with target size (Tripathy & Cavanagh, 2002), further ruling out masking effects, which do scale with spatial frequency in both fovea and periphery (Polat & Sagi, 1993). This implicates a non-selective spatial pooling region of relatively fixed size that may correspond to the spatial resolution of visual attention (He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001; Tripathy & Cavanagh, 2002), the integration stage of later visual processes (Chung, Levi & Legge, 2001) or the region over which grouping and segmentation processes combine texture (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001).

While much is known about the spatial characteristics of crowding in static stimuli, relatively little is known about the temporal characteristics of crowding. Studies of the temporal properties of crowding have reported that crowding decreases as exposure duration increases (Plant & Tripathy, 1997; Tripathy & Cavanagh, 2002) and that flanking elements with a 50 ms stimulus onset asynchrony (SOA—i.e. flanking elements presented 50 ms after target onset) crowd more than other SOAs (Ng & Westheimer, 2002). Retinal image motion caused by unstable fixation in observers with albinism or congenital nystagmus increases crowding effects (Chung & Bedell, 1995; Pascal & Abadi, 1995). However, when nystagmus is simulated in normal vision observers with saw-tooth motion jitter, crowding is elevated only in some observers, indicating that jerky retinal image motion may only account for part of the increase in cowding in observers with unstable fixation (Chung & Bedell, 1995). For targets in smooth motion, the spatial scale of visual analysis shifts to lower spatial frequencies as speed increases (Brown, 1972; Chung & Bedell, 2003; Demer & Amjadi, 1993; Hoffman, Rouse, & Ryan, 1981; Kline, 1994; Long & Johnson, 1996; Long & Penn, 1987; Long & Zavod, 2002), which explains why letter acuity decreases as target speed increases (Brown, 1972; Chung & Bedell, 2003; Demer & Amjadi, 1993; Hoffman et al., 1981; Kline, 1994; Long & Johnson, 1996; Long & Penn, 1987; Long & Zavod, 2002), but measurements of crowding with stimuli in smooth motion have not yet been reported. Here we extend previous studies by examining how crowding is affected by smooth target motion at a range of speeds and eccentricities.

2. Methods

2.1. Apparatus

Stimuli were generated on a Macintosh G4 computer with software adapted from the VideoToolbox routines (Pelli, 1997) and were displayed on a LaCie ElectronBlue 22″ monitor at a frame rate of 75 Hz and a mean luminance of 50 cd/m^2, calibrated with a Minolta photometer. The display measured 36 cm (1152 pixels), 27.2 cm vertically (874 pixels), and was 230, 115 or 57 cm from the observer, in an otherwise dark room.

2.2. Stimuli and procedure

The target was a black (<1 cd/m^2) sans serif upper case letter T oriented up ↑, right →, down ↓ or left ←. We elected to use an oriented T target in preference to a standard set of letters, such as the SLOAN optotypes (Sloan, 1951), because confusions among the target letters increase noise in the data (Bennett, 1965; Gervais, Harvey, & Roberts, 1984). However in trial runs with a nine alternative identification task with a subset of the 10 SLOAN letters (letter K was removed by random choice for use with a nine button response box), we found the same effects reported below. The target was presented in isolation when measuring acuity and was surrounded with up to four flanking "+" symbols in crowding conditions. The target and flanking symbols were always composed of a horizontal and a vertical line of equal length, the line width was equal to one fifth of the length, in line with the SLOAN optotype convention. Illustrations of the stimuli are shown in Fig. 1; note that these illustrations are not to scale.

The target was presented on a notional annulus with a radius of 256 pixels, centred on the middle of the display. The observer's viewing distance was 230, 115 or 57 cm so that the eccentricity of the annulus was 2°, 4° or 8° respectively. The initial location of the target on the annulus was random and then updated on successive video frames so that it moved along the annulus at the required angular speed. The orientation of the target was fixed throughout the trial. The angular displacement of the target letter was 0, 2, 4 or 8 rotational°/video frame around the display centre (i.e. angular shift around the clock). These rotational angle displacements correspond to retinal speeds in degrees of visual angle of 0, 5 10 and 21/s at 2° eccentricity; 0, 10, 21 and 42°/s at 4° eccentricity; and 0, 21, 42 and 84°/s at 8° eccentricity,

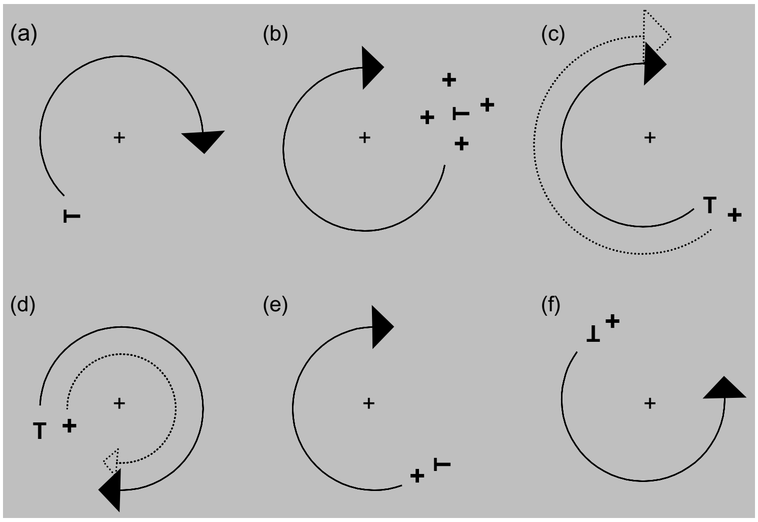

Fig. 1. Illustration of the stimuli. In acuity and crowding experiments, observers were required to identify the orientation of an upper case letter T oriented up ↑, right →, down ↓ or left ←. For acuity experiments, the target was presented in isolation (a) and its size was varied to determine acuity threshold. For crowding experiments, the target letter at threshold size was surrounded on all sides (b), or on one of its four sides (c–f) by moving flanking + symbols of the same size. The single flankers could be positioned (c) more peripheral, (d) more foveal, (e) ahead or (f) behind the target. The separation between target and flanking stimuli was varied to determine the extent of spatial interference. Target and flanking stimuli of constant orientation were set in motion at a range of speeds along a notional annulus in a clockwise or anti-clockwise direction about central fixation, as suggested by the arrows. See text for detailed explanation.

The direction of motion (clockwise or anti-clockwise) was random across trials to minimise the build-up of direction-specific adaptation (Mather, Verstraten, & Anstis, 1998). Stimuli were presented for 107 ms with abrupt onset and offset. This brief duration, together with the random starting location of the target, prevented observers from making eye movements to the target as these take a minimum of 150–200 ms to initialise and execute to a known location (Carpenter, 1988).

The observers were two of the authors (PB and AS) both experienced psychophysical observers with visual acuity of 6/6 or better and both practised the task extensively before formal data collection. Observers viewed the display monocularly with an eye-patch covering their non-dominant eye. Their task was to fixate the central cross and to identify the orientation of a target letter by pressing one of four buttons on a response box corresponding to the four possible target orientations. Auditory feedback was provided following incorrect responses.

2.3. Acuity

Identification acuity was measured by varying the size of the target T in a four alternative orientation identification task. The target size was under the control of a QUEST staircase (Watson & Pelli, 1983) that concentrated observations at a size producing 82% correct responses. Spatial anti-aliasing was achieved by linear interpolation. Five rotational speeds (0, 1, 2, 4, 8 rotational°/frame) were randomly interleaved on the same run. Thresholds at three eccentricities (2°, 4° or 8°) were measured in random order by changing the viewing distance between runs. The raw data from at least four runs of 32 trials per speed and eccentricity were combined and fitted with a cumulative normal function by least χ^2 fit, from which threshold size was determined at the 95% correct level and 95% confidence intervals were estimated on this point by conventional methods (Press, Teukolsky, Vetterling, & Flannery, 1992). This high threshold level was chosen to ensure good peak performance in subsequent crowding trials (see below). Although our staircase did not concentrate observations on this point, the psychometric function was well sampled over at least four independent runs. However, even if target size were slightly under or overestimated this should not affect the spatial extent of crowding at a given eccentricity (Tripathy & Cavanagh, 2002).

2.4. Crowding

The spatial interference zone around target elements was measured in a four alternative identification task in which observers identified the orientation of the target T that was surrounded on up to four sides by flanking "+" symbols. The spatial extent of interference was measured with four flanking elements, one placed on each of the four sides of the target. The two-dimensional shape of the interference zones was measured by placing a single flanking element on one side of the target and repeating this procedure for each of the four sides.

The size of the target was fixed at the 95% threshold acuity size at each speed and eccentricity as estimated from the results of the acuity tasks. This high threshold ensured that when the flanking elements were not exerting any crowding effect, orientation identification was near perfect. The target started at a random location on the annulus and then moved along the annulus by the required angular displacement as in the acuity experiment. Flanking elements were the same size as the target (i.e. they were scaled with speed and eccentricity in line with target acuity) and also moved along a circular path around fixation at the same angular speed as the target and at fixed orientation, like the target. The flanking elements were positioned in one of four locations:

(1) *peripheral*: on an annulus of greater radial eccentricity than that of the target
(2) *foveal*: on an annulus of lesser radial eccentricity than that of the target
(3) *leading*: on the same annulus as the target but ahead of its motion trajectory
(4) *trailing*: on the same annulus as the target but behind its motion trajectory

Schematics of the stimuli are shown in Fig. 1. Moving illustrations of acuity and crowding stimuli (not to scale) are available on PB's web site (www.ucl.ac.uk/~smgxpbe/crowding.html). Target and flanking elements moved at the same *angular* speed and with a constant separation between them in degrees of visual angle on any trial. Thus the whole target and flank configuration moved around the annulus, smoothly rotating to maintain constant orientation and eccentricity.

The centre–centre separation between flanking elements and the target was under the control of a QUEST staircase (Watson & Pelli, 1983) designed to concentrate observations at a separation producing 75% correct responses for detecting the orientation of the target T—note that chance performance was 25% and peak performance was 95% correct. The direction of motion of the target was random across trials. This means that a more clockwise flanking element was separately coded as *leading* (as in Fig. 1e) or *trailing* (as in Fig. 1f), depending on the direction of motion of the target. While it is possible that the use of a single target forces observers to identify which of the two is the target and which the flank, this uncertainty is evenly distributed across conditions and should not affect one condition more than any other. Five crowding conditions (all four flankers, one peripheral, one foveal, one leading or one trailing flanker) were randomly interleaved in a single run. Spatial interference zones at five rotational speeds (0, 1, 2, 4, 8 rotational°/frame) and three eccentricities (2°, 4° or 8°) were measured in random order across runs. The raw data from at least four runs of 32 trials per crowding condition, speed and eccentricity were combined and fitted with a cumulative normal function by least χ^2 fit, from which the extent of spatial interference zones was determined at the 75% correct level.

3. Results

3.1. Acuity

Fig. 2 shows letter acuity in arcmin for two observers (PB in Fig. 2a and AS in Fig. 2b) at three eccentricities (2°, 4° and 8°, see legend) and five speeds (0, 1, 2, 4, and 8 angular°/frame). Error bars show ±95% confidence intervals. There is a significant decrease in acuity with eccentricity ($F_{(2,2)} = 41.3$, $p = 0.024$) and with speed ($F_{(4,4)} = 15.6$, $p = 0.01$). The fall-off in acuity with eccentricity is in good agreement with standard data for static stimuli (Millidot, 1966). Previous studies of acuity

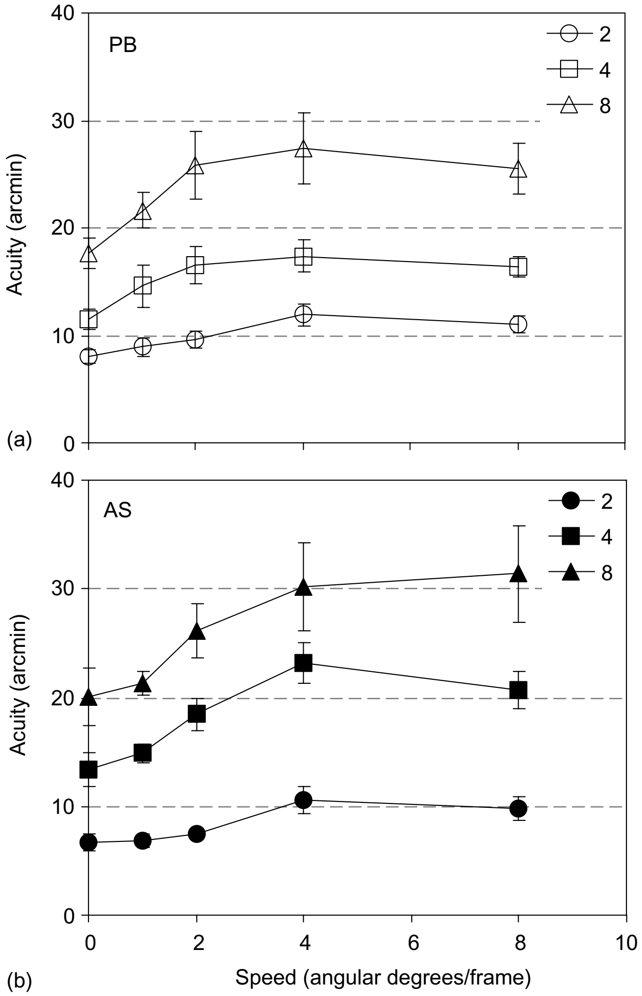

Fig. 2. Resolution acuity as a function of speed and eccentricity. The graphs show for two observers the letter size in arcmin at which the orientation of an isolated T stimulus were correctly identified on 95% trials—termed threshold acuity size—as a function of speed (shown on the *x* axis) and eccentricity (shown by the legend). Error bars show ±95% confidence intervals.

for dynamic targets have shown a fairly monotonic reduction in acuity with speed (Brown, 1972; Chung & Bedell, 2003; Demer & Amjadi, 1993; Hoffman et al., 1981; Kline, 1994; Long & Johnson, 1996; Long & Penn, 1987; Long & Zavod, 2002). We find that acuity is lower for moving targets, but there is little reduction in acuity for speeds above approximately 4°/frame. We attribute this difference to the constant exposure duration and eccentricity maintained here, but not in previous studies (see Section 4).

3.2. Crowding

Fig. 3 shows the extent of the spatial interference zones in degrees of visual angle measured with four flanking "+"s for two observers (PB and AS) at three eccentricities (2°, 4° and 8°, see legend) and five speeds (0, 1, 2, 4, and 8 rotational°/frame). Error bars show ±95% confidence intervals. For both static and moving stimuli, there is a significant increase in the size of spatial interference zones with eccentricity ($F_{(2,2)} = 175.1$, $p = 0.006$), in line with many previous studies with static stimuli (Bouma, 1970; Chung, Levi & Legge, 2001; Hess et al., 2000; Jacobs, 1979; Latham & Whitaker, 1996b; Loomis, 1978; Strasburger et al., 1991; Toet & Levi, 1992; Wolford & Chambers, 1984). The size of crowding zones is not significantly affected by motion at any target speed ($F_{(4,4)} = 0.32$, $p = 0.86$).

Fig. 4 shows the two-dimensional shape of the spatial interference zones in degrees of visual angle measured with a single flanking "+" for two observers (PB in Fig. 4a and AS in Fig. 4b) at three eccentricities (2°, 4° and 8°, indicated by the separation along the y axis) and five

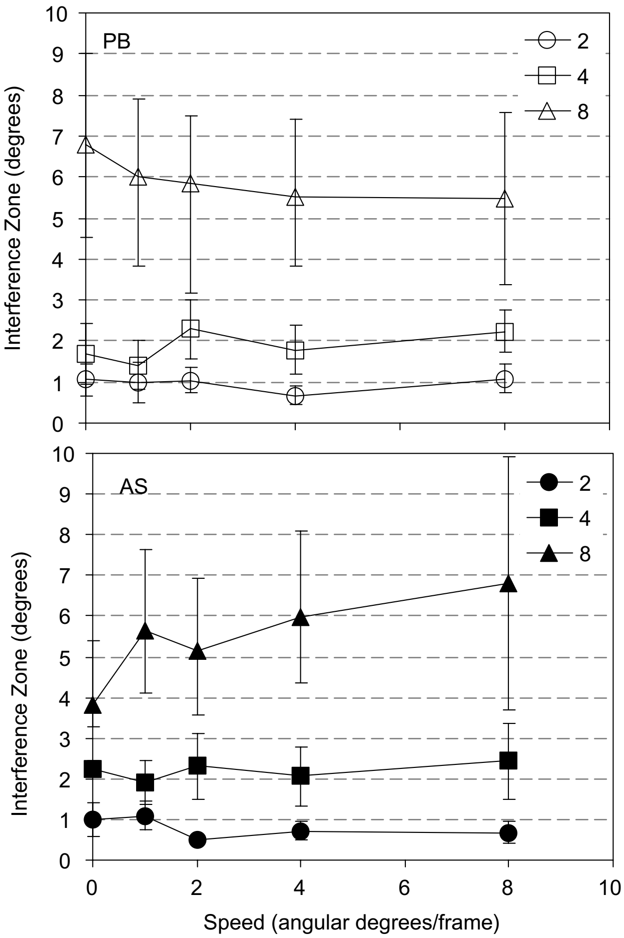

Fig. 3. Spatial interference zones as a function of speed and eccentricity. The graphs show for two observers the separation between a target and four flanking stimuli in degrees of visual angle at which letters of threshold acuity size were correctly identified on 75% trials as a function of speed (shown on the x axis) and eccentricity (shown by the legend). Error bars show ±95% confidence intervals.

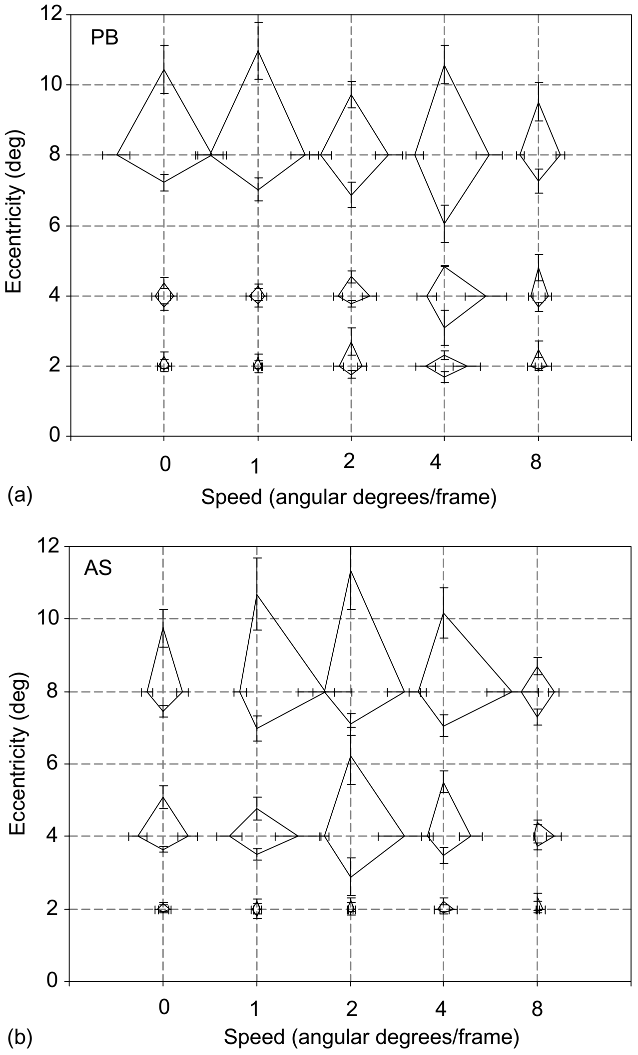

Fig. 4. Two-dimensional shape of spatial interference zones as a function of speed and eccentricity. The figures show for two observers the separation between a target and a flanking stimulus in degrees of visual angle at which letters of threshold acuity size were correctly identified on 75% trials as a function of speed (shown on the x axis) and eccentricity (shown by the y axis). Error bars show ±95% confidence intervals.

speeds (0, 1, 2, 4, and 8 angular°/frame, indicated by the separation along the x axis). The spatial interference zones are plotted in degrees of visual angle horizontally and vertically at each point, indicated by the y axis in degrees of visual angle. Error bars show ±95% confidence intervals along each dimension. A comparison between the mean size of the spatial interference zones in each dimension across all conditions and observers confirms that interference zones along radial axes about fixation are on average 1.3 times greater than zones tangential to this radius ($t_{29} = 3.7, p < 0.001$), consistent with previous data for static targets (Toet & Levi, 1992). Furthermore, the spatial interference zones of peripheral flanking elements are 2.2 times greater than flanking elements that are more foveal ($t_{29} = 6.1, p < 0.001$). For moving targets averaged across speeds and observers, the interference zones of flanking elements that are ahead of the target (right data points in Fig. 4) are 1.9 times larger than those of elements trailing behind it ($t_{23} = 2.9, p < 0.02$).

4. Discussion

4.1. Dynamic acuity

Our acuity results (Fig. 2) are consistent with the classic observation that resolution acuity decreases for high contrast letters presented in the peripheral visual field, (Aubert & Forster, 1857). We also found that the visibility of moving targets is less than that of static targets, in line with many previous studies (Brown, 1972; Chung & Bedell, 2003; Demer & Amjadi, 1993; Hoffman et al., 1981; Kline, 1994; Long & Johnson, 1996; Long & Penn, 1987; Long & Zavod, 2002). However, in our study acuity was relatively unaffected by motion at speeds up to 84°/s (8° rotational/frame at 8° eccentricity), whereas others have reported a montonic fall-off in acuity for speeds up to 100°/s (Demer & Amjadi, 1993). Previous studies have used targets in linear motion, so that either the maximum eccentricity of the target increased with speed, which itself reduces acuity (Aubert & Forster, 1857), or its exposure duration decreased, which also reduces acuity (Baron & Westheimer, 1973). Our study used annular motion at constant eccentricity and fixed exposure duration and so does not confound these parameters.

4.2. Dynamic crowding

The acuity data were used to scale the resolution target and flanking elements at each speed and eccentricity in the crowding experiment. The size of spatial interference zones (the centre–centre spacing between the target and flanking elements where identification of the target letter T orientation reaches 75% correct) was not affected by target motion at any speed. For vernier (Chung & Bedell, 1998; Chung & Bedell, 2003; Chung, Levi & Bedell, 1996) and letter identification (Chung & Bedell, 2003) tasks with moving stimuli, it has been shown that the elevation of spatial thresholds for moving broad band and filtered stimuli is consistent with a shift in analysis towards lower spatial frequencies. It might therefore be expected that crowding zones would not remain constant (as we find) but would increase with speed, in line with the coarser scale used to identify the target. However, it has also been shown recently that in peripheral visual field, the extent of spatial interference does not scale with spatial frequency of narrow-band target letters (Chung, Levi & Legge, 2001; Levi, Hariharan et al., 2002) or with the size of broad-band letters (Tripathy & Cavanagh, 2002), so it does not necessarily follow that a shift in the scale of visual analysis will cause a corresponding change in the spatial extent of crowding. Therefore our results are not inconsistent with a shift in the scale of target analysis with speed, but we are unable to draw any conclusions about the spatial frequencies used for target identification in our broad-band stimuli.

4.3. Relative or absolute size of spatial interference zones?

The extent of the spatial interference is often expressed relative to the size of the resolution target (for example in terms of the number of letter bar-widths) rather than in absolute visual angle, to facilitate comparison of the extent of spatial interference across the visual field. However as the size of the resolution target increases with eccentricity (to compensate for the fall off in acuity), it is difficult to determine whether the increase in crowding with eccentricity depends on changes in visual processing across the visual field or on changes in the size of the target. To disentangle these factors (Tripathy & Cavanagh, 2002), measured spatial interference zones at 5° and 10° eccentricity with targets of fixed size. Targets were held at their resolution acuity limit by varying contrast instead of size. With these stimuli, the authors showed that the size of spatial interference zones was constant at each eccentricity when expressed in terms of visual angle, regardless of the size of the target letter. In the present study, the size of resolution target in our crowding experiment increased with speed and eccentricity (Fig. 2). When the size of the spatial interference zones is expressed as visual angle (Fig. 3) it is invariant of speed at each eccentricity. If we re-expressed spatial interference zones in terms of target size therefore, spatial interference zones would covary with speed. In agreement with (Tripathy & Cavanagh, 2002), an absolute scale for spatial interference zones allows the data to collapse to a fixed-size spatial interference zone at each eccentricity, regardless of target size (in Tripathy and Cavanagh's case) and regardless of speed (in our case).

4.4. Two-dimensional shape of spatial interference zones: 1 radial elongation

For stationary stimuli, Toet and Levi (1992) have measured the two-dimensional shape of spatial interference zones with pairs of flanking letters on opposite sides of the target. Flanking letters that were aligned with fixation along radii were more effective crowders than flankers positioned tangentially around the target. Thus, the two-dimensional shape of crowding zones was found to be elliptical, elongated radially about central vision. The authors speculate that this asymmetry could be linked to the radial organisation of ocular dominance columns in the primary visual cortex (V1) of some primates (Hubel, Wiesel, & Stryker, 1978; LeVay, Hubel, & Wiesel, 1977), which means that retinotopically adjacent V1 cortical receptive fields are closer (in mm of cortex) along circular/tangential axes than along radial axes.

We confirm Toet and Levi's finding for static targets and also show that the elliptical shape of crowding zones is independent of motion at any speed. With single flanking elements we were also able to plot the shape of crowding zones on each of the four sides of the target and found that single elements that were further from fixation were more effective crowders than those closer to fixation. This surprising finding has been noted previously (Chastain, 1982; Chastain, 1983; Banks, Larson, & Prinzmetal, 1979). It seems paradoxical that a peripheral flanker that is less visible than a foveal flanker (owing to the fall off in acuity) is nevertheless a more effective crowding stimulus. This phenomenon has previously been attributed to increasing positional uncertainty in peripheral visual field that can cause confusions between the target and flanker, especially when they are spatially similar (Chastain, 1982). We further speculate that both results may be related to cortical magnification, in which the surface area of primary visual cortex dedicated to processing the visual field falls approximately logarithmically with eccentricity (Daniel & Whitterbridge, 1961; Tootell, Silverman, Switkes, & De Valois, 1982). This organisation means that equidistant interactions in cortex represent interactions in visual space that increase with eccentricity (Motter, 2003). Thus crowding may arise from equidistant cortical effects that produce m-scaled effects in the visual field.

4.5. Two-dimensional shape of spatial interference zones: 2 trajectory elongation

We also found that a flanking stimulus moving ahead of the target crowded more than a flanking stimulus that trailed the target. It is possible that this result simply reflects temporal summation within the visual system (Barlow, 1958; Burr, 1981), so that the motion blur of a leading flanker masks the target and disrupts its identification, while the motion blur of a leading target masks the trailing flank and does not affect target identification. However, if this were the case, we would expect crowding to increase with speed because motion blur increases with the speed of sharp objects (Burr, 1980; Hammett, Georgeson, & Gorea, 1998); but we do not find this effect.

A number of recent reports have argued that motion signals are combined preferentially along the trajectory of motion. For example, (Verghese, McKee, & Grzywacz, 2000) measured detection thresholds for a triplet of dots moving coherently in a background of random-walk noise dots. The target dots were easier to detect when their motion was parallel to their orientation than when their motion was perpendicular to it, although we have recently reported that this effect is contingent on foveal positioning of the target, (Bex, Simmers, & Dakin, 2003). Similarly, using "path-finder stimuli", (Ledgeway & Hess, 2002) reported that under a limited range of conditions, contours composed of isotropic elements moving parallel with the axis of the contour were more visible than contours composed of elements moving perpendicular to it. These studies suggest that under some conditions, motion signals are preferentially combined along the trajectory of moving objects and that consequently elements moving parallel to their orientation are more visible than those moving perpendicular to it. This suggests that our leading/trailing target-flanker configurations may have been more visible than our foveal/peripheral target-flanker configurations. However we do not know a priori whether a more visible target and flanker configuration should produce more or less crowding than a less visible configuration. Studies of the effects of contrast on crowding show that crowding effects increase with contrast (Kothe & Regan, 1990; Pascal & Abadi, 1995; Simmers, Gray, McGraw, & Winn, 1999; cf. Fine, 2003). If anything, this would lead us to expect more crowding for more visible leading/trailing target-flanker configurations than for less visible foveal/peripheral configurations, but we found the opposite effect.

Recently, Verghese and McKee (2002) reported that a contrast increment is more detectable when it occurs at the end of a motion trajectory than at its beginning and that the effect is due to improved efficiency in monitoring motion detectors at anticipated target locations and to consequent changes in contrast gain at these positions. It is therefore possible that a similar change in contrast gain could form the basis of the difference we find in crowding between trailing and leading flanking elements. However, owing to the equivocal effects of "visibility" discussed above, again we cannot predict a priori how this might affect crowding.

4.6. Relevance to studies of reading dynamic text

The increase in crowding effects in peripheral vision is thought to be a major factor contributing to slow and inefficient reading in the peripheral visual field (Latham & Whitaker, 1996a; Leat, Li, & Epp, 1999; Rubin & Turano, 1994). Reading speeds in central and peripheral visual field can be significantly improved with dynamic text, and this can be of particular benefit for low vision observers with central field loss (Rubin & Turano, 1994). Reading speed increases by around 50% for low vision observers with central field loss and by as much as 200% for observers without central field loss (Fine & Peli, 1995; Fine & Peli, 1998; Rubin & Turano, 1992; Rubin & Turano, 1994) with rapid serial visual presentation (RSVP) text. However, when text is temporally modulated with motion (scrolled text) reading rates in normal vision observers are reduced by 30% (Buettner, Krischer, & Meissen, 1985) to 44% (Legge, Ross, Luebker, & LaMay, 1989) while reading rates increase by 15% in low vision observers (Legge et al., 1989). A comparison of the relative reading rates of scrolled and RSVP text show that at moderate text size, normal vision observers read RSVP 1.3 times faster than scrolled text, but both are read at the same rate by low vision observers with central or peripheral field loss (Fine & Peli, 1995; Fine & Peli, 1998). At large text sizes (>8x acuity reserve) all normal vision observers and many low vision observers read RSVP text faster than scrolled text (Fine & Peli, 1998). It has been suggested that a reduction in the need to make eye movements forms the basis for the improvement in reading speeds with RSVP (Rubin & Turano, 1994). Inter- and intra-word eye movements and eye movements to the beginning of new lines are obviated by RSVP, but the same might also be expected with scrolled text. The reason for the benefits of RSVP and scrolled text over stationary text therefore remain unclear. Although we have not tested reading performance in this study, it has recently been shown that letter identification limits reading performance, rather than whole word information (Pelli, Farell, & Moore, 2003). Our data with moving targets at exposure durations too brief for fixational eye movements show that motion does not reduce crowding effects among letters within words and suggests that differences in crowding between moving and static text are not the basis for reading benefits with dynamic displays.

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