Seven myths on crowding[1]

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Abstract

Crowding research has become a hotbed of vision research and some fundamentals are now widely agreed upon. It is highly likely that you would agree with the following statements. 1) Bouma's Law can be sensibly stated as saying that 'critical distance for crowding is about half the target's eccentricity'. 2) Crowding is a peripheral phenomenon. 3) Crowding increases drastically and steadily with eccentricity (as does the minimal angle of resolution, MAR). 4) Crowding asymmetry: For the nasal-temporal asymmetry of crowding, Bouma's (1970) paper is the one to cite. 5) The more peripheral flanker is the more important in crowding. 6) Critical crowding distance corresponds to a constant cortical distance in primary visual areas like V1. 7) Except for Bouma (1970), serious crowding research pretty much started in the 2000s. I propose the answer is 'no!' to most all of these questions. So should we care? I think we should, before we write the textbooks for the next generation.

Introduction

In 1962, the ophthalmologists James Stuart and Hermann Burian published a study on amblyopia where they innocently used a term – perhaps not uncommon among ophthalmologists – to describe why standard acuity test charts are mostly unsuitable for amblyopic subjects: On most standard charts, as ophthalmologists know, optotypes on a line are too closely spaced such that amblyopic subjects (and young children) may receive too low an acuity score. In writing, this had been reported earlier by the Danish ophthalmologist Holger Ehlers[2] (Ehlers, 1936, 1953). Because amblyopic vision is unlike blurred vision, it has often been compared to peripheral or indirect vision for illustration, and indeed the same phenomenon with closely spaced patterns occurs there. Independently, however, and unknown to ophthalmologists and optometrists, the phenomenon had already been studied quite - extensively, first in Gestalt psychology and then nearly exclusively in experimental psychology. At the time when I became interested in it (1988), there were twenty major papers on the subject under a number of key words. Yet vision research, with a few exceptions, was 'not interested'. Neither were the cognitive sciences, visual neuroscience, optometry, and – as it seemed to me – everybody else.

Things changed in the nineties and noughties. In our first paper on the subject we asked what mechanisms might underlie crowding (1991, 1995); then He et al. (1996) pointed to the role of spatial attention, and in particular Denis Pelli started projects on crowding and published a

[1] Talk slides for this paper are published as preprint in Strasburger, 2018b.

[2] "When one is testing amblyopic children with isolated letters or E's, the visual acuity recorded is often much better than with the ordinary test chart. If the visual field is crowded with letters, the area of the visual field in which the letters can be recognized narrows. This is very easy to demonstrate, as I showed at the Congress of Scandinavian Ophthalmologists in 1936."

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monumental paper, covering all the basics (Pelli et al., 2004). Crucially, however, Pelli drew attention to the fact that, contrary to common wisdom, crowding is much more important for pattern recognition than is acuity; it overrides the latter even in foveal vision, widely held to be superior because of its outstanding acuity (Pelli et al., 2007; Pelli & Tillman, 2008).

Small as it might seem, the shift of emphasis away from (inherently low-level) acuity to (inherently higher-level) crowding amounts, as I see it, to nothing less than a paradigm shift. It does away with centuries of core assumptions in visual perception (cf. Strasburger & Wade, 2015b), namely that good vision comes down to good acuity, or, more generally, that a reductionist approach is always the best way for solving a scientific problem. The *acuity myth* is everywhere. We find it in driving licence regulations (where acuity tests are often the only strict psychometric requirement for a driver's license), or when a textbook presents a trivialized dichotomy of parvo (*P*) and magno (*M*) systems in which the *P* system is supposedly specialized on pattern recognition because of its high resolution and small receptive fields. Thomas Kuhn in *The Structure of Scientific Revolutions* (Kuhn, 1962) explains that research traditions in science often pervade through many decades (or perhaps centuries?), adding more and more detail to a scientific narrative until suddenly, within a few years, the viewpoint shifts radically and something new starts. The shift of emphasis in human and primate pattern recognition from acuity to crowding might just represent such a turn.

Perception is a standard and often required subject in psychology, medicine, and other curricula and so there are quite a few excellent textbooks on *perception* and on the senses. A particularly well-known book covering all the senses is Goldstein's *Sensation and Perception*. Here is what the 6th edition (2002) says about crowding: Nothing. The book does cover acuity, cortical magnification, and peripheral vision. To top it off, acuity and crowding are confused as shown in Figure 1 (6th edition, 2002, p. 57; 9th edition, 2013, p. 43). The author might be excused in that vision is not his primary field of study. But that excuse does not transfer to the German editions which were edited by well-known vision scientists (see Figure 1). My other favourite, *Basic Vision* by Snowden, Thompson & Troscianko, a more recent perception textbook for the visual modality, explains cortical magnification and shows Anstis's visual demonstration of that in its first edition (2006), but skips crowding. The new, 2nd edition (2012): Still no mentioning of crowding. The section on peripheral vision (pp. 113–117) shows a modified version of Anstis's magnification chart and explains scaling and cortical magnification (the chart is the more impressive but misleading version of Figure 6b, below, with a caption[3] that warrants understanding why it is wrong).

[3] The caption says "An eye chart in which letters in different parts of our visual field have been scaled to make them equally legible. The size has to double approximately every 2.5° in order to do this". This innocent sounding description is formidably incorrect in two ways: (1) The 2.5° value is meant to be the E_2 value, but its definition is misunderstood. It is defined as a doubling of the *foveal* value, not a doubling *every* 2.5°. The doubling rule would lead to an exponential increase ($y=2^n \cdot s_0$ with *n* being the number of increments), not to a linear function as required. (2) The graph shows the exaggerated version (see Statement 3), so the E_2 value would be only one tenth of 2.5°.

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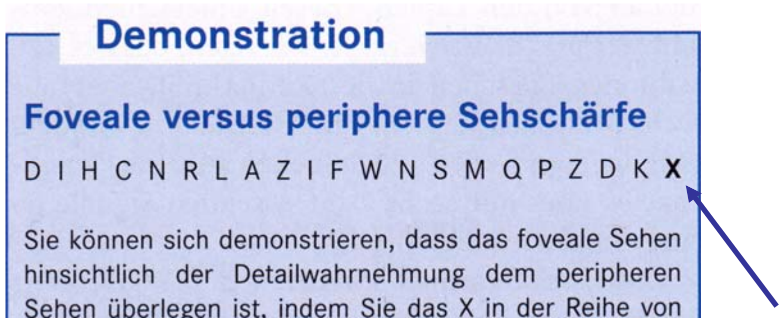
Demonstration

Foveale versus periphere Sehschärfe

D I H C N R L A Z I F W N S M Q P Z D K **X**

Sie können sich demonstrieren, dass das foveale Sehen hinsichtlich der Detailwahrnehmung dem peripheren Sehen überlegen ist, indem Sie das X in der Reihe von

Figure 1. Confusion of acuity and crowding in Goldstein's 7th German edition (2008), chapter Neural processing, subchapter Why we use cone vision for details, p. 50. Accompanying text: "You can demonstrate to yourself that, with respect to perceiving detail, foveal vision is superior to peripheral vision by fixating the X …". The same graph is shown in the English 6th edition (2002, p. 57) or the 9th edition (2013, p. 43). The added arrow shows where to fixate.

Thus, either crowding is after all much less important for vision in general than I personally believe it is. Or, now is the time that crowding will enter our textbooks and curricula. The frequent publications, talks and symposia at vision conferences, workshops, theses, and in short the observation that crowding is nowadays a vision-research household item, would suggest the latter. In that case, it matters that, in the sudden flood of interest, quite a number of misconceptions on the topic have propagated. To ensure, therefore, that these are kept at bay, in particular in the perception books that are to come, here is an attempt to pinpoint a number of simple beliefs that, upon more scrutiny, turn out to be misleading or just wrong. It is the fourth in a series of – slightly tongue-in-cheek – *myths* presentations in vision research (Strasburger, 2017b; Bach, 2017; Strasburger, 2017a; Strasburger, 2018b, *Preprint)*, and I trust more will follow[4].

Interestingly, there is no catchy German word for *crowding* and so the English term has entered German-language scientific writing. Conversely (and on the light side), the German germane *wimmelbild* (*wimmeln* = to swarm with) is sometimes seen on English pages instead of the "Find Waldo" / "Where's Wally" catch phrases, and in any case those crowded images are about to develop into an art form of their own (Figure 2).

[4] On the more general subject of myhts in neuroscience and what they have to do with occult passions, you will enjoy *The frog's dancing master* by Piccolino & Wade (2013).

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Figure 2. Example of a German wimmelbild (Caro Wedekind, about the 31st Chaos Communication Congress (31C3) in Hamburg; Wedekind, 2014).

So let's get started. You would agree with the following seven statements (one in each section) – wouldn't you?

On Bouma's Law

Statement 1). *Bouma's Law can be sensibly stated as saying that 'critical distance for crowding is about half the target's eccentricity'.* – **No**.

Agreed, a take-home message should be plain, simple, and concise. That said, however, one needs to make sure the simplicity is not deceptive and leads to wrong conclusions. In the above statement, the crucial point is the qualifier *about*. Mostly it is assumed the qualification refers to the factor 0.5 in Bouma's rule-of-thumb equation,

$$d = 0.5\varphi \qquad (1)$$

(where *d* is critical distance – the minimum distance between target and flanker below which crowding occurs – and φ is eccentricity in degrees visual angle). Indeed, that factor may vary quite a bit, roughly between 0.3 and 0.7, as Pelli et al. (2004) have shown, while the linearity holds for almost all visual tasks. There is a more important slur, however, a limitation of the rule's generality that becomes apparent when considering a particularly important case for

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crowding: foveal vision and reading. The eccentricity angles (φ) are small there and the precise meaning of critical distance becomes important. Bouma (1970a) specified *d* as the threshold of internal or empty space between target and flankers; today's authors prefer to specify flanker distance as measured centre-to-centre, for various reasons (Figure 3).

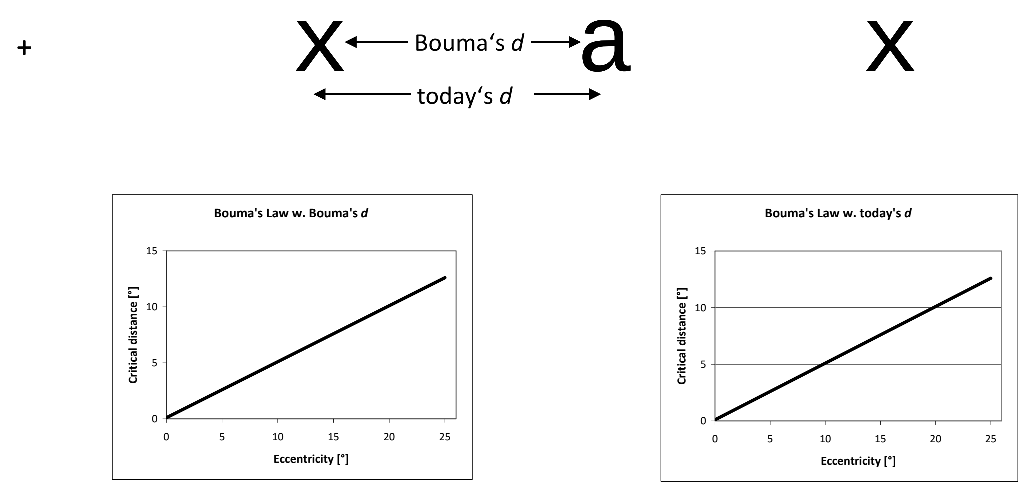

Figure 3. Top: Bouma's crowding stimulus arrangement. On the left is a fixation point (+), to the right of which a target letter (a) appears that is surrounded by two equally-spaced flankers (x). Target and flankers are in Times-Roman font, with a variable number of fixed-width spaces in between. Bottom: Bouma's law shown over the range that crowding has been studied so far, with Bouma's empty-space definition of critical distance (left) and today's centre-to-centre definition (right). The difference at that scale is too small to be visible.

At small eccentricity angles, where (by Bouma's rule) flankers at the critical distance are close to the target, that difference of specification matters (Figure 4). With Bouma's empty-space definition, critical distance is *proportional* to eccentricity (pink line in Figure 4a). With today's centre-to-centre definition, in contrast, critical distance is *not* proportional to eccentricity; it is just a little bigger, by one letter width. The difference is seen in Figure 4a, where the blue line is shifted relative to the pink line. The blue line has a positive axis intercept and represents a linear law, not proportionality. With the centre-to-centre definition in eq. (1), the stimulus configuration would become ridiculous in the centre fovea: proportionality would imply that target and flankers are at the identical location in the centre; just off the centre, target and flankers would overlap, as shown in Figure 4b. Importantly, it is *not* what Bouma said.

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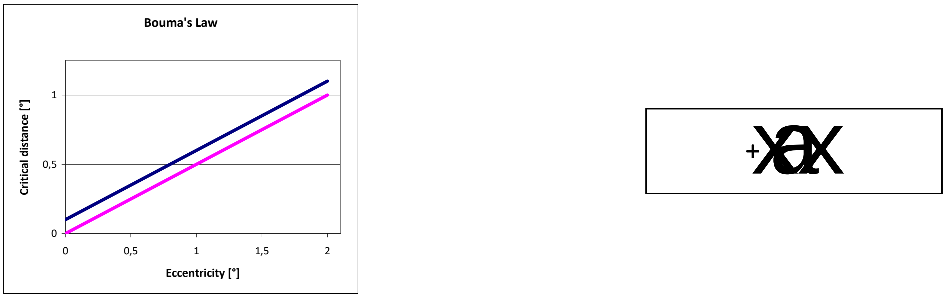

Figure 4. (a) Comparison of Bouma's law with critical distance defined as empty space (pink) vs. centre-to-centre (blue). (b) An absurd stimulus configuration that would result from an incorrect statement of Bouma's Law.

To sum up, in today's terminology Bouma described a linear law, not proportionality:

$$d = 0.5\varphi + w, \qquad (2)$$

where *w* is letter width. We warned against this fallacy before (e.g. Strasburger et al., 2011, p. 34). Notably, Weymouth (1958) had already pointed out the importance of that difference.

But perhaps you just find equation (1) more elegant and appealing? In that case, note that equation (2) is formally equivalent to *M*-scaling. Isn't that beautiful? It has ramifications of its own that we wrote about elsewhere (Strasburger & Malania, 2013; Strasburger, 2018a, *Manuscript)*, and that I will come back to, below.

Crowding and peripheral vision

Statement 2). *Crowding is a peripheral phenomenon.* – **No**.

Crowding is of course highly important in the visual periphery. It is often even said to be *the* characteristic of peripheral vision (e.g. when amblyopic vision is likened to peripheral vision). Yet (and that is mostly overlooked) in a sense crowding is even more important in the fovea since, there, it is the bottleneck for reading and pattern recognition. Pelli and coworkers have pointed that out most explicitly (Pelli et al., 2007; Pelli & Tillman, 2008). Beware in that context that the fovea is larger than one is mostly aware of: its diameter is around 5 deg visual angle (Polyak, 1941, Wandell, 1995). When vision scientists speak of 'foveal vision' they are talking about the situation where the observer fixates. For example, when an optometrist measures visual acuity, the result refers typically to the short moment when the gap of the Landolt ring is at the fovea's very centre. It is then that maximum acuity is achieved and one minute of arc, or better, is resolved. Yet in the rest of the fovea, acuity is much lower. Phrased differently, resolving Landolt gaps is not of foremost interest for reading. Letter sizes in normal reading far exceed the acuity limit. In normal reading, about one word fits into the fovea; so with an average length of roundabout five letters the letter width is about half a degree – more than 30 times the acuity limit.

Within the fovea, crowding is further not only present off-centre (i.e. for indirect vision), it is also present down to the fovea's very centre. That has been controversial for a time but that some kind of lateral interaction occurs in the very centre is now well established (Flom, Weymouth, & Kahnemann, 1963; Coates & Levi, 2014; Siderov, Waugh, & Bedell, 2014; see

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Coates & Levi, 2014 for review). The interaction effect "of foveal acuity targets occurs within a fixed angular zone of a few min arc" (3′–6′) (Siderov, Waugh, & Bedell, 2013; Siderov et al., 2014, p. 147). However, the characteristics of that interaction might be different from those further out, and Coates & Levi, 2014 and Siderov et al., 2014 consequently (like Flom et al., 1963) speak of *contour interaction*. Namely, whereas crowding appears to be mostly independent of letter size (Strasburger et al., 1991, Pelli, Palomares, & Majaj, 2004), that seems less so the case for the fovea centre and is described by Coates & Levi (2014) as conforming with a two-mechanism model in which the critical spacing for foveal contour interaction is fixed for S<5′ and proportional to target size for S>5′ (Figure 5a). Coates & Levi (2014) call that behaviour the *hockey stick model*.

Let us consider for a moment how the hockey stick model is related to Bouma's Law. The model describes the situation at 0° eccentricity. For a target at that location of up to 5′ size, critical spacing is a constant 5′. The stimuli in Siderov et al. (2013) are a Sloan letter surrounded by bars, so the statement could be rephrased as saying that, for Sloan letters below 5′ size, the bars need to be located not nearer than at 5′ eccentricity. Yet that statement appears to me as rephrasing an independence of letter size, up to 5′ at 0°.

Above 5′ letter size, critical spacing is proportional to target size according to the hockey stick model. Now note that (by definition) the spacing is adjacent to the target, and with increasing target size, its location will move outward at the same rate. Thus, that statement from the hockey stick model implies that critical spacing is proportional to the gap's eccentricity. Yet this is a restatement of Bouma's law (with the empty-space definition; see Statement 1 above)!

Taken together, the hockey stick model is thus compatible with the independence of target size at 0° eccentricity (up to 5′ size), and with Bouma's Law at 0°. Targets at 0° just need to be small enough that they do not touch the location of the critical gap.

The question remains as to what Bouma's Law looks like at very small eccentricities, i.e. just off the centre. At 0°, critical gap size is about 5′–6′ of arc – does it, with increasing target eccentricity, increase linearly from there or does it first stay constant for a few minutes of arc, and then increase (Figure 5b)? The hockey stick model (though speaking only about 0° eccentricity) appears to suggest the former: Consider first a 12′ target at 0° eccentricity. Critical gap size, according to the model, is greater than 6′ (by proportionality), say it is 9′ (i.e. the proportionality factor is 0.5). The gap starts at 12′ (by definition). Now imagine a 6′ target at 6′ eccentricity. The gap, again, starts at 12′ (by definition). Since the gap location is the same as before, it is likely that critical gap size is the same as in the first example, i.e. 9′.

As a corollary, that would imply that Bouma's Law with the empty-space definition is not strictly proportionality after all, but has a small vertical offset of 6′ (i.e. 0.1°) (Figure 5b). A direct test of Bouma's Law at very small eccentricities (0 – 0.2°), together with a test how it fits in with the hockey stick model, will be interesting.

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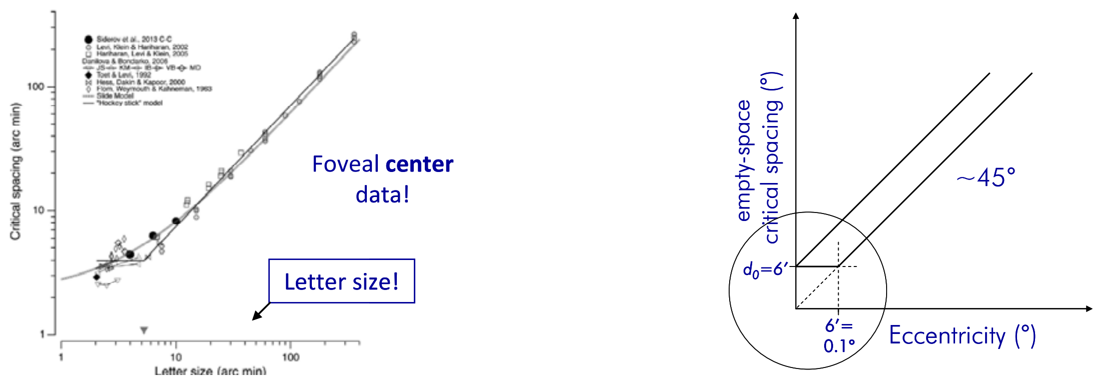

Figure 5. (a) Coates & Levi's hockey stick model, describing the dependence of centre-to-centre critical spacing on target size. The filled circles show Siderov et al.'s (2013) data for Sloan letters surrounded by bars. (b) Possible shapes of Bouma's Law in the visual field's very centre (with a slope of 0.5).

In summary, crowding is not just a peripheral phenomenon. It is present, and in a sense even more important, in the visual field centre.

That said, however, crowding has as yet only been tested within the centre 25°-radius visual field. That is a far cry from the "real" periphery – in perimetry and ophthalmology the periphery only starts from 30° eccentricity outwards; the area within that is referred to as the "central visual field". The periphery in that sense is several times the central field in area, and extends, on the temporal side, to around 107° eccentricity (Rönne, 1915 ; Traquair, 1938). Note: Not 90° as said in most modern textbooks – but that's another myth story (Strasburger, 2017b; Bach, 2017).

Crowding across eccentricity

Statement 3). *Crowding increases drastically and steadily with eccentricity, just like acuity decreases.* – **Hmm**.

A tricky one! First of all, acuity decreases drastically towards the periphery, doesn't it? Just look at textbook illustrations. Well, acuity does decrease – i.e. the minimal angle of resolution (MAR) increases – but that happens only moderately. The myth of steep incline, reproduced in most every textbook that mentions the periphery, is based on the famous demonstration charts by Anstis (1974). There are three charts in that paper that illustrate the change of scale across the visual field brought about by cortical magnification (Figs. 2, 3, and 4, reproduced here in Figure 6). The actual enlargement of peripheral letter size to accommodate cortical magnification is shown in Anstis's Fig. 2 (Figure 6a). However, since the letters are approximately at the acuity limit in that chart and are thus hard to recognize, Anstis enlarged the letters tenfold in the chart of Fig. 3, for better visibility. That chart looks more appealing and intuitive and is the one typically chosen elsewhere for illustrations of how the periphery differs from "ordinary" (i.e. foveal) vision. But as Rosenholtz (2016) has pointed out in an enlightening paper, that enlargement dramatically overemphasizes the peripheral performance decline. This is because sizes are enlarged but eccentricities are not. The overemphasis is by the same (whopping) factor of ten. The misunderstanding arises because the chart is mostly understood too literally (Anstis

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probably never intended that). It is a good example of how pictures can lead us wildly astray.

Figure 6. The three charts of Anstis (1974), Fig. 2, 3, and 4, for illustrating cortical magnification. Letter sizes according to an estimate of the cortical magnification factor (left). Letter sized increased tenfold (middle). Same letter sizes but more letters added to increase crowding (right).

But there is more. Anstis's Fig. 3 (here Figure 6b) is intended to show single-character recognition, i.e. to illustrate the increase of the MAR. The letter spacings, measured centre-to-centre, may appear adequately spacious for preventing crowding at first. Yet because letter sizes, by design, are not equal, one needs to look at the empty spaces. An inspection of those shows that, even though for each letter the respective outward neighbour leaves around 50% of (that letter's) eccentricity φ empty space, this is not the case for the *inward* neighbour which only leaves between 20% and 45% of φ space. Thus, there is quite a bit of crowding in that graph. Thus, crowding in effect further overemphasizes the alleged effect of MAR-increase in the chart.

For a rough estimate of the actual rate of increase, assume an E_2 value of 1° for Landolt acuity and an resolvable gap size of S_0 = 1′. That implies a slope of 1′/1° or 1/60 = 0.017 deg/deg for gap-size vs. eccentricity (Strasburger, Rentschler, & Jüttner, 2011, eq. 8). At roughly 2%, that increase is really moderate indeed.

While we are at it, let us look at Anstis's third chart (Fig. 5, shown in Figure 6c), which is for an illustration of crowding. That one is really crowded! Empty spaces are obviously far below the critical ½ φ. Letter sizes are as before, so acuity plays no role. Yet the large letters might lead one to believe that that is what the periphery needs. So the reader might be puzzled what, precisely, the graph shows.

Now to the question how crowding increases with eccentricity. The increase is certainly at a much steeper rate than for acuity: By Bouma's Law, critical spacing increases at a rate of ½ deg/deg, which is thirty times the rate for MAR. It is much, much steeper.

However, that is the increase of critical distance, not that of crowding! Crowding, by definition, is the reduction of recognition performance brought about by the presence of flankers. We thus need to convert *critical distance* to *recognition performance*.

To do that we need the psychometric function of letter recognition vs. flanker distance. It is surprisingly difficult to find data for that in the crowding literature, even though it is basic for

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letter crowding. For the present purpose I chose data from Yeshurun & Rafal (2010, shown in Figure 7, red line) that were collected as a baseline for a different question. The task was recognizing the orientation of a gray letter T on a darker background amidst flanking letters H below and above, at variable flanker distance (size: 1.05°×1.05°, Michelson contrast: 10%; eccentricity: 9°). There were four possible orientations, so chance level was 25%. The figure is modified for didactic purposes, with both axes starting at zero and dashed lines added to indicate chance level and minimum flanker distance. The red dashed line further shows the likely shape of the psychometric function at low flanker distances (since proportion-correct p_c cannot go below 25% as would be implied by the connecting straight lines, unless there were artifacts).

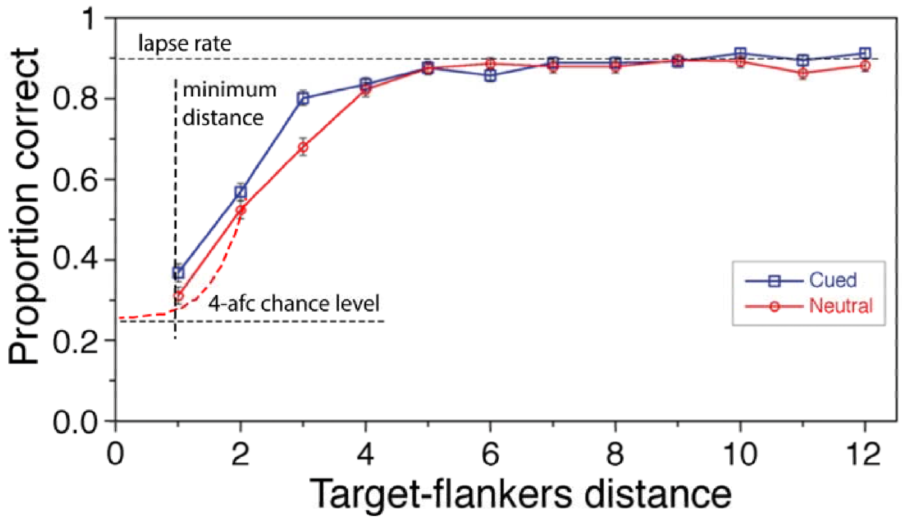

Figure 7. Psychometric function of letter-T recognition vs. flanker distance (red line; disregard the blue line). Modified from Yeshurun & Rafal (2010, Fig. 5).

Now, from that psychometric function (p_c vs. flanker distance), together with Bouma's Law (which describes critical distance vs. eccentricity), we can infer how crowding behaves with increasing eccentricity. Note first that, for a general answer to that question, distances between objects can be assumed as being on average independent of visual eccentricity ("the scene does not care where you look at", so to say). Examples where that is approximately the case would be letters on a printed page, or people in a crowd. We further assume that, in the direction where we look, that distance is below the critical crowding distance, so that recognition is unaffected by crowding. Performance p_c is then at 100% minus the lapse rate λ (top right in Figure 7). Figure 8a shows the same function schematically, to explain terms. It shows proportion-correct (p_c) vs. flanker distance with the empty-space definition. Best performance is $1-\lambda$ and is obtained at sufficiently large flanker distances. Crowding, defined as the reduction of performance, is shown as the downward arrow from that level. That reduction, i.e. the length of that arrow, is $1 - \lambda - p_c$.

The reduction is shown directly in Figure 8b. The figure is obtained from Figure 8a by re-scaling the y-axis and flipping the graph horizontally and vertically, so that crowding (the downward arrow in Fig. 8a) goes upwards and flanker distance d goes backwards. The y-axis now shows

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crowding.

Finally, observe that Figure 8b can be re-interpreted as showing eccentricity φ or critical spacing d_c instead of $–d$ on the x axis: The psychometric function in Figure 7 or Figure 8b shows proportion-correct vs. $(d–d_c)$, i.e. vs. flanker distance minus critical distance:

$$p_c = \Phi(d-d_c) \qquad (3)$$

(where Φ is a sigmoid function). Crowding is then

$$c = 1 - \lambda - p_c = 1 - \lambda - \Phi(d-d_c). \qquad (4)$$

Since the distance d between objects is assumed to be a constant and critical distance d_c is variable (it varies with eccentricity), this is a function of $–d_c$ (i.e., d_c going backwards), centred at the mean object distance d (as in Figure 8b). Critical distance, expressed as empty space, is proportional to eccentricity φ by Bouma's Law (eq. 1),

$$d_c = \beta\varphi \qquad (5)$$

with some scaling factor β around 0.5. The resulting function for crowding vs. eccentricity is thus

$$c = 1 - \lambda - \Phi(d - \beta\varphi) \qquad (6)$$

as shown in Figure 8b.

For an intuitive understanding inspect Figure 8b again, starting from the left. There is no crowding (c = 0) in the centre of the visual field for the average task (like reading this paper). When eccentricity is increased, critical distance (understood as empty space) increases proportionally but recognition performance stays unaffected because critical distance is below the objects' distance. At some eccentricity, shown as dashed line, critical distance becomes equal and then larger than the distance between the objects in the scene. Crowding increases rapidly there, according to a sigmoid psychometric function like that in Figure 7 or 8a. A little further out in the visual field, behaviour is limited by chance performance and does not change further.

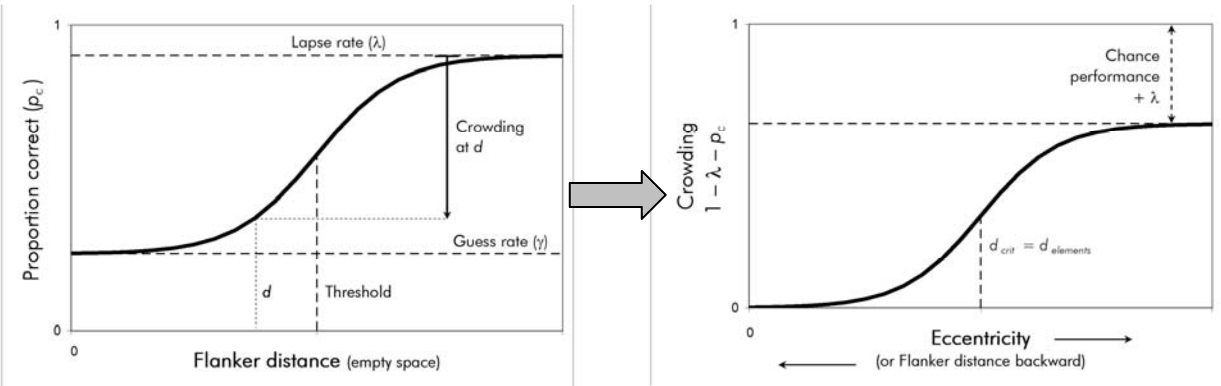

Figure 8. Schematic depiction of crowding, as defined standardly, i.e. as the impairment of recognition performance by the presence of flankers. (a) Psychometric function for proportion-correct performance in a crowding task, as in Figure 7. The effect of crowding, at some flanker distance d, is seen as the downward arrow on the right, starting from best performance (1–λ). (b) Crowding as in figure part a, as a

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function of eccentricity.

So, back to the initial question: Does crowding increase drastically and steadily with eccentricity? Yes and no. Up to some eccentricity, there is no crowding in most scenes. A little further out, there is full crowding (Figure 8b).

Crowding asymmetry

Statement 4). *For the nasal-temporal asymmetry of crowding, Bouma's (1970) paper is the one to cite.* – **No**.

Crowding is asymmetric, as is well known, with the more outward flankers playing a different role than the more inward ones. People like to cite Bouma's (1970) paper for that asymmetry. Indeed, Herman Bouma mentions it in that short *Nature* letter – but warning that these are only pilot data on the asymmetry and noting it only as an aside at the end of the letter. The credit must instead go to Norman Mackworth: Mackworth (1965) reported the asymmetry several years earlier and it is to him whom Bouma refers to (both in his 1970 and his 1973 paper).

Mackworth (1965):

This *end-of-the-line effect was followed up in another study with 20 further Harvard and Radcliffe Ss*. The tachistoscopic conditions were identical except that now only five letters were presented in 100 msec. Even two extra noise letters can drastically reduce recognition scores for three wanted letters provided the two noise letters are added just outside the wanted letters. They have much less effect when they are placed just inside the wanted letters; the recognition score *doubles* when the wanted letters are *outside* the unwanted. This suggest that the scanning of the visual image … may be undertaken from the outside inward …

Bouma (1970):

A *pilot experiment* indicated that, in the /xa/ situation, the adverse interaction is stronger if the interfering /x/ is at the peripheral side of the unknown letter rather than the foveal side. The area of interaction is thus not quite circular around the position of the unknown letter but, rather, *egg-shaped* towards the retinal periphery (compare Mackworth, *Psychon. Sci.*, 3, 67, 1965).

Figure 9. Quotes on the nasal-temporal asymmetry of crowding, by Mackworth (1965) and Bouma (1970). Emphasis added.

To put Mackworth's quotation in perspective, an example for the end-of-the-line effect that he refers to is shown in Figure 10 (Haslerud & Clark, 1957). Performance for the recognition of individual letters in a word depends heavily on its respective position within the word. Even though subjects fixated on the words (probably somewhere near their centre; Rayner, 1979) recognition for the first and last letter was best, followed successively by the more inward ones. Word length was about 7.6° visual angle, so letter width was around 0.6° and the location of the first and last letter at about 3.5° eccentricity. Thus, already in these early experiments, the influence of eccentricity (i.e. reduced acuity) was shown to be outweighed, by far, by less

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crowding due to the empty space at the beginning and end of a word. Bouma (1973) reported a similar result, which is discussed by Levi (2008). Precursors of such experiments were by Erdmann, Dodge, and Wagner (see Haslerud & Clark, 1957).

Bouma has also not really followed up much on the nasal-temporal asymmetry; it is the left-right asymmetry and the recognition of inward versus outward letters in a word that he writes about later (Bouma, 1973). The nasal-temporal asymmetry has been thoroughly investigated though by Estes & Wolford (1971), Estes et al. (1976), Krumhansl (1977), and Chastain (1982, 1983) (and more recently by Bex, Dakin & Simmers (2003), Petrov & Popple, 2007, Dayan & Solomon, 2010, and quite a few more). Unfairly, the older papers often get no credit in the vast current crowding literature (see Strasburger & Malania, 2013, and Strasburger, 2014, Levi, 2008, and Dayan & Solomon, 2010 for reviews of the asymmetries).

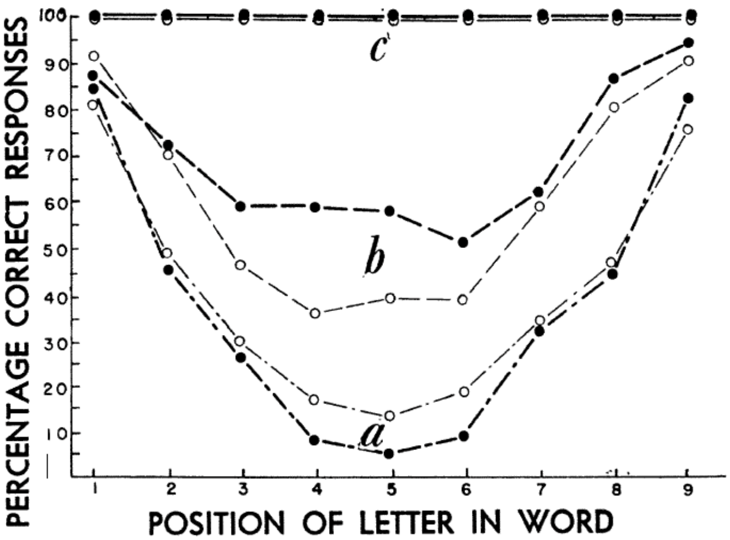

Figure 10. End-of-the-line effect that Mackworth refers to (Haslerud & Clark, 1957). Letter recognition in 7.6°-wide nine-letter words. Open symbols: women; filled: men. *a:* fragmentary responses; *b:* incorrect; *c:* correct.

Statement 5). *The more peripheral flanker is the more important one in crowding.* – **Yes and No**.

There appears to be wide agreement now that in that asymmetry the more peripheral flanker exerts more "adverse interaction" than the one on the foveal side, as Bouma (1970) has put it. Bouma thus suggests that "the area of interaction is […] egg-shaped towards the retinal periphery", and this fits together well with the interaction zones drawn by Toet & Levi (Toet & Levi, 1992).

But that unanimity is deceiving; the conclusion that the more peripheral flanker is always the more important one is not that clear-cut as sometimes suggested. Even though the superior recognizability of the peripheral flanker is probably uncontroversial, the consequence of that for crowding is unclear. The opposite asymmetry was reported by Chastain (1982), who found that, with respect to the effects of similarity and confusion, the *inward* flanker plays the more important role. He further pointed out that the confusability increases with eccentricity. Furthermore, Krumhansl's (1977) data, when re-analysed by Chastain (1982, p. 576), also supported the reverse asymmetry, counter to what was stated in Krumhansl's text.

An opposite asymmetry was further reported more recently by Strasburger & Malania (2013),

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with an informal model for explanation in Strasburger (2014). The data there (shown in Figure 11a) are from a reanalysis of results for the character-crowding task in Strasburger (2005). Part of the crowding effect (up to about 30%) was shown to result from whole-character confusions between target and a flanker. Contrary to our expectations it turned out that confusions with the *inward* flanker were more frequent than with the outward one. Moreover, that difference depended on eccentricity; it increased for the inward, but not the outward, flanker. Note that – since whole-letter confusions are not the only reason for crowding, such a result does not contradict a stronger net inhibitory effect of the more peripheral flanker under suitable conditions.

Several informal theories have been put forward to explain the asymmetry in crowding. The suggestion in Strasburger (2014) is to account for the conflicting results by adding the influence of a mechanism not yet considered in the crowding literature: *feature binding* (von der Malsburg, 1981, Wolfe & Cave, 1999). According to hitherto proposed accounts for explaining crowding, like Wolford's (1975) classical feature-perturbation model, or modern statistically constrained pooling theories (Freeman, Chakravarthi, & Pelli, 2012, Balas, Nakano, & Rosenholtz, 2009, Keshvari & Rosenholtz, 2013), flanker attributes get mixed-in with the target letter in the crowding task, such leading to "false" percepts. However, such models do not, up to now, distinguish between (erroneously attributed) individual features, and (confusions with) whole characters. Yet there is quite a bit of evidence that whole-letter confusions are not just the sum of feature misallocations (Estes et al., 1976, Wolford & Shum, 1980, Strasburger et al., 1991; Huckauf & Heller, 2002, Chung, Legge, & Ortiz, 2003, Strasburger, 2005, Vul, Hanus, & Kanwisher, 2009, Strasburger & Malania, 2013). This is where I suggest the concept of binding comes in. However implemented, it is an algorithm or system characteristic that decides which features belong together and which do not. The proposal is now that such feature binding decreases with visual eccentricity. Inward flankers are thereby more "stable" and tend to interfere as a whole, whereas peripheral flankers tend to mix in features with the target (Figure 11b).

This is not to say that confusions, in whole or in part, are the whole story. Crowding mechanisms other than confusions most likely play a part and could also be stronger more peripherally (compared to centrally). They could lead to a stronger overall interference of the peripheral flanker, consistent with the majority of findings on the asymmetry.

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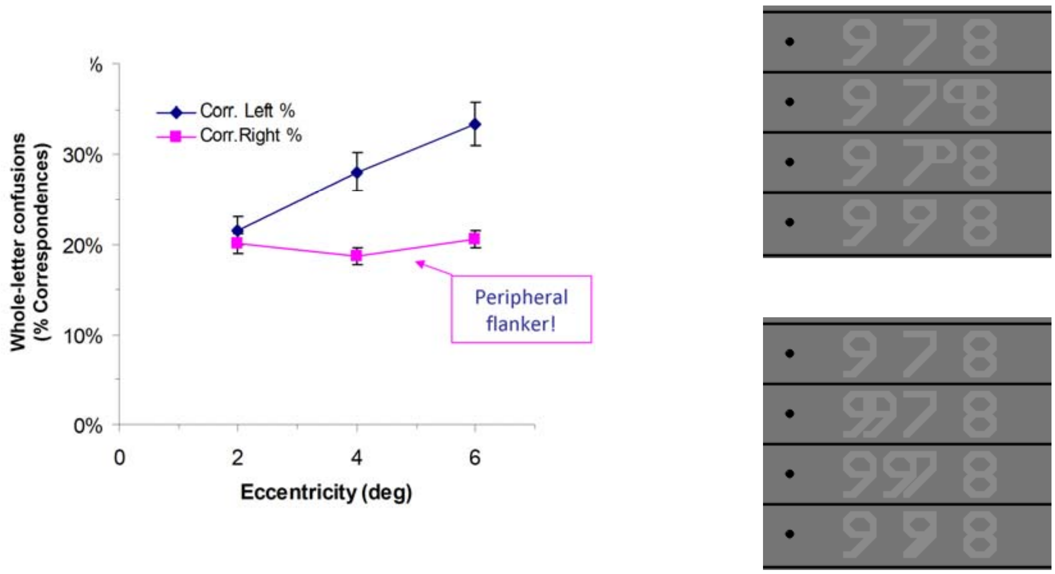

Figure 11. (a) Reverse asymmetry in a crowding task reported in Strasburger & Malania, (2013, Fig. 8a) (modified). Confusions with the more central, but not the more peripheral, flanker depend on eccentricity. (b) Cartoon, as a memory hook for the mechanisms: (top) A peripheral letter part moving inward; (bottom) The nasal flanker moving outward.

So in sum, neither of the flanking endpoint letters is just more “important” for crowding; the suggestion here is that peripherally and centrally located flankers play a somewhat different role, and that the extent of that specific interference depends on eccentricity. How, exactly, will need more research.

Crowding in the cortical map

Statement 6). *Critical crowding distance corresponds to a constant cortical distance in V1 and other primary visual cortical areas.* – Probably: **No**.

Crowding is a cortical phenomenon; we know that since Flom, Weymouth & Kahnemann (1963). And crowding is about how objects are spatially arranged in the visual field and how close they are. Now since the primary cortical visual areas are retinotopically organized, that spatial arrangement translates to the primary cortical areas and how close the objects’ representations are there. The question that naturally arises then is how the critical distance for crowding in the visual field translates to the distances in the cortical map(s). What is the equivalent of Bouma’s Law in the primary visual cortex?

Motter & Simoni (2007) proposed Bouma’s Law translates to a constant critical distance on the cortical map. Pelli (2008) presented a mathematical derivation of that constancy, based on Schwartz’s (1980) logarithmic cortical mapping rule. The answer to the questions is of practical use for research and Mareschal, Morgan, & Solomon (2010) applied that rule to a question and analysis of theirs. A different, non-constant rule was derived by us (Strasburger et al., 2011).

The constant cortical distance rule is appealing for its elegance and its derivation is mathematically sound. It needs to be qualified, however: the constancy does not hold for the fovea! Indeed, Schwartz (1980) has proposed two logarithmic mapping functions, a general and

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a simplified version. The latter is undefined in the centre (it omits a constant term in the log's argument) and was meant to be applied only for eccentricities sufficiently above zero. It is the latter version, together with the simplified Bouma Law (Figure 3a), that Pelli (2008) used in his derivations (and he warns against this limitation).

A corrected rule that includes the fovea is presented in Strasburger (2017c, 2018a), shown in Figure 12 below. It is derived from the general cortical location function which, as shown in that paper, can be stated as

$$d = \frac{d_2}{\ln 2} \ln\left(1 + E / E_2\right). \quad (7)$$

The dependent variable *d* in that equation is the distance on the cortical map from the retinotopic centre (d_0) in millimetres, and the equation expresses it as a function of eccentricity *E* in the visual field (in degrees visual angle). There are two parameters in the equation, E_2 and d_2. E_2 is Levi's value specifying at which eccentricity in the visual field the foveal value (of, e.g., MAR) is doubled (Levi, Klein, & Aitsebaomo, 1984, Strasburger et al., 2011; see Footnote 2 above). The newly proposed parameter d_2 is the counterpart of that in the cortical map: the distance of E_2's representation in the map from the retinotopic centre (which is roughly at the occipital pole).

From the location function (eq. (7)) one can derive critical distance on the cortical map. One simply inserts the locations for target and flanker at the critical distance, for some target eccentricity *E,* and takes the difference. After simplification one obtains

$$\kappa = M_0 E_2 \ln\left(1 + \frac{\delta_0}{E_2} \frac{(1 + E / \hat{E}_2)}{(1 + E / E_2)}\right). \quad (8)$$

Critical distance on the cortical map is denoted by kappa (κ) in the equation. Further parameters are M_0*:* the cortical magnification factor at the retinotopic centre (about 30 mm/°), δ_0*:* the centre-to-centre critical distance for crowding in the fovea centre (in deg visual angle), and a new parameter, $\hat{E}_2$*:* the E_2 value for critical distance in Bouma's Law. About the latter: As said above (after eq. (2)), Bouma's Law is a linear function and is formally equivalent to *M*-scaling. It can thus be written in the standard E_2-notation as

$$\delta = \delta_0 (E / \hat{E}_2 + 1). \quad (9)$$

The $\hat{E}_2$ in that equation is the eccentricity (in the visual field) at which the critical-distance value in the centre (δ_0) doubles (or, equivalently, the eccentricity increment at which critical distance increases by the foveal value δ_0).

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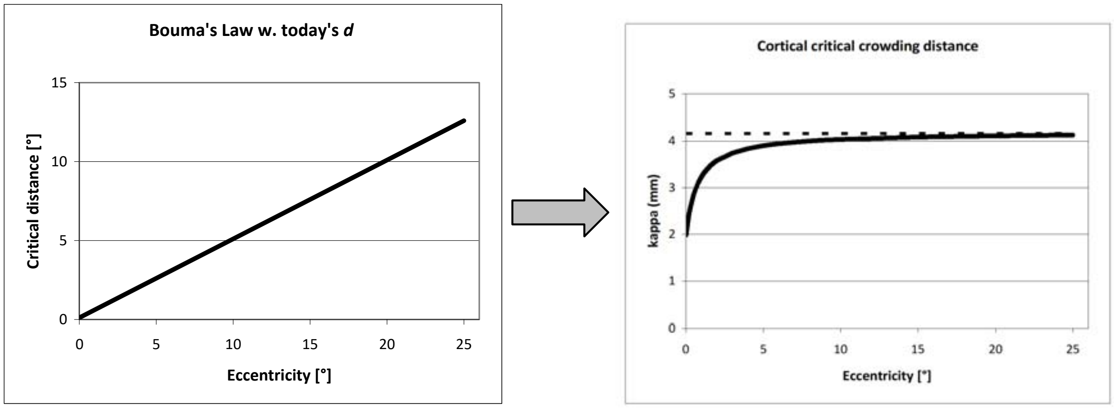

Figure 12. (a) Bouma's Law in the visual field and (b) its cortical equivalent, i.e. how it translates to the cortical map in a primary visual area (Strasburger, 2017c, Strasburger, 2018a).

The graph of eq. (8) is shown in Figure 12b. Critical distance for crowding on the cortical map starts at some value in the centre (i.e. at E=0°), and then – depending on the ratio $E_2/\hat{E}_2$ (the ratio of the respective E_2 values for MAR and crowding) – quickly increases to a different value that it reaches asymptotically. Constancy is thus reached above some eccentricity value (probably somewhere just outside the fovea). This equation can thus be seen as a generalization of Pelli's result which now also covers the case of central vision and reading.

Crowding research

Statement 7). *Except for Bouma's (1970) paper, serious crowding research pretty much started in the 2000s.* – (Not really.)

Crowding is 'quite the rage' in vision research these days. A very modern enterprise it is, with serious research starting in the 2000s. OK, this is a misguided caricature but I do feel that the numerous papers from the sixties and seventies, as well as the initial paper by Korte (1923), do not get the credit they deserve. Not only are they rarely cited, most scholars also do not know what is said there (and are blissfully unaware that what is reported in them might precede their own ideas – after all, it is good scientific practise to give the credit to who said it first).

A simple reason for that neglect might have been that other terms for the phenomenon, or similar or related phenomena, were the popular ones at those times:

Lateral masking, lateral inhibition, lateral interference, interaction effects, contour interaction, and *surround suppression* (Strasburger et al., 1991).

It could be argued that these terms denote different things, and indeed there are important differences. Yet all attempts so far at finding clear criteria for unambiguous and consistent classification schemes (e.g. for deciding between whether an effect shows crowding or masking) have not as yet led to reliable distinctions. That is not to say such attempts were fruitless and not important, quite to the contrary. It just means that we still lack a coherent theory of crowding. In any case, one is surprised what shows up with these terms in standard search machines.

Another, somewhat trivial reason for the neglect, at least for a while, was that full-text versions of older papers were not available online. In the comparably young history of crowding research that change of reading and writing habits away from printed material had an influence. Digitization of the older literature is not yet complete; that of 19th-century and before is still an ongoing process.

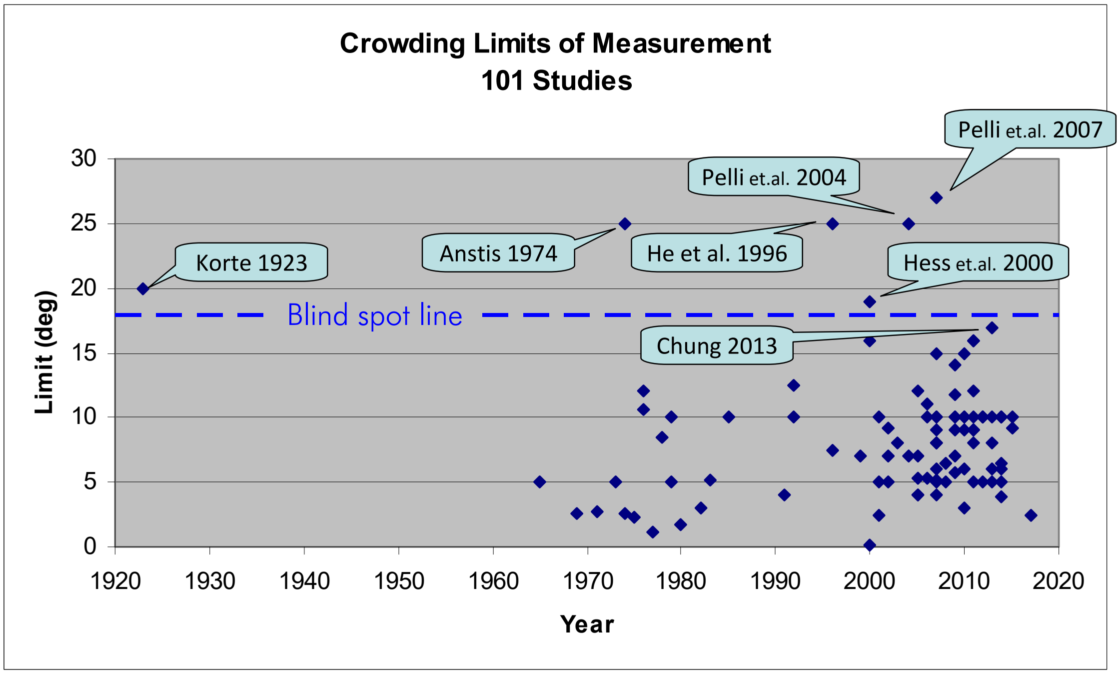

Figure 13. Essential crowding literature from 1923 to 2004. Abscissa: year of publication; ordinate: eccentricity in the visual field up to which crowding was studied in the paper. (References in Figure 14.)

Figure 13 shows a chart of crowding literature up to the present day. Beware it is by no means complete. The x-axis shows the year of publication and the y-axis the maximum eccentricity (on a meridian or in the visual field) up to which data were reported. The horizontal dashed line at 18° marks the blind spot as an anchor.

There are four points that I wish to make: (1) The vast majority of studies are concerned with quite small eccentricities (cf. Myth #2). (2) The maximum eccentricity up to which crowding was studied is a mere 25°. Given that pattern recognition is possible in most all of the visual field, and is proven to be so up to about 80° for simple forms (Collier, 1931, Menzer & Thurmond, 1970, Strasburger, 2017a), one wonders what crowding is like beyond 25°. (3) @2000: Indeed, research took off at around 2000 but there are quite a number of publications in the seventies to nineties. (4) The time span between 1923 and 1962 is curiously empty (Ehlers 1936, 1953, are not listed since they have no data). Filling the gap might need more digging in the older literature. Another reason, however, could be the expulsion of Gestalt psychologists from Germany, who were those interested in visual phenomena at that time. Figure 14 gives the references for the papers in that graph. Those in blue print might be seen as landmark papers (but this is of course a subjective view).

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Crowding research, 1923 – 2004

Autors	Year	Limit °	Autors	Year	Limit °
Korte	1923	**20**	**Levi**, Klein & Aitsebaomo	1985	10
Ehlers	1936/'53	--	**Strasburger**, Harvey & Rentschler	1991	4
Stuart & Burian	1962	0	Geiger, Lettvin & Zegarra-Moran	1992	12.5
Mackworth	1965	5	**Toet & Levi**	1992	10
Shaw	1969	2.6	**He**, Cavanagh & Intriligator	1996	**25**
Townend, Taylor & Brown	1971	2.8	Higgins, Arditi & Knoblauch	1996	7.5
Bouma	1973	5	Huckauf, Heller & Nazir	1999	7
Anstis	1974	**25**	Hess, Dakin, Kapoor & Tewfik	2000	19
Wolford & Hollingsworth	1974	2.6	Liu & Arditi	2000	0.2
Wolford	1975	2.3	Xing & Heeger	2000	16
Andriessen & Bouma	1976	12	Chung, Levi & Legge	2001	5
Estes, Allmeyer & Reder	1976	10.6	Fine	2001	10
Krumhansl & Thomas	1977	1.2	**Parkes**, Lund, Agelucci, Solomon, Morgan	2001	2.5
Loomis	1978	8.5	Huckauf & Heller	2002	7
Banks et al.	1979	5	Levi, Hariharan & Klein	2002	5
Jacobs	1979	10	Tripathy & Cavanagh	2002	9.2
Wolford & Shum	1980	1.7	Bex et al.	2003	8
Chastain	1982	3	Huckauf & Heller	2004	7
Wolford & Chambers	1983	5.2	**Pelli**, Palomares & Majaj	2004	**25**

Figure 14. Crowding literature from 1923 to 2004 shown in Figure 13. Blue print: Particularly important papers. The last column shows (as before) the eccentricity in the visual field up to which crowding was studied.

References in Figure 14

Korte, 1923; Ehlers, 1936; Ehlers, 1953; Stuart & Burian, 1962; Mackworth, 1965; Shaw, 1969; Townsend, Taylor, & Brown, 1971; Bouma, 1970b; Anstis, 1974; Wolford & Hollingsworth, 1974;Wolford, 1975; Andriessen & Bouma, 1976; Estes et al., 1976; Krumhansl & Thomas, 1977; Loomis, 1978; Banks & Larson, 1979; Jacobs, 1979; Wolford & Shum, 1980; Chastain, 1982; Wolford & Chambers, 1983; Levi, Klein, & Aitsebaomo, 1985; Strasburger et al., 1991; Geiger, Lettvin, & Zegarra-Moran, 1992; Toet & Levi, 1992; He, Cavanagh, & Intriligator, 1996; Higgins, Arditi, & Knoblauch, 1996; Huckauf, Heller, & Nazir, 1999; Hess, Dakin, Kapoor, & Tewfik, 2000; Liu & Arditi, 2000; Xing & Heeger, 2000; Chung, Levi, & Legge, 2001; Fine, 2001; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Huckauf & Heller, 2002; Levi, Hariharan, & Klein, 2002; Tripathy & Cavanagh, 2002; Bex et al., 2003; Huckauf & Heller, 2004; Pelli et al., 2004.

Crowding research before 1923

Ehlers (1936) in the above list was the first documented use of the term *crowding*; the Gestalt psychologist Wilhelm Korte was the first who provided an analysis of phenomena in indirect vision including phenomena related to crowding (Korte, 1923; see Strasburger, 2014 for an excerpt). What happened before that?

Surprisingly, phenomena that we would today interpret as *crowding* were already described in writing a thousand years ago, by Al-Haytham (965–1039) (Strasburger & Wade, 2015a). This is as early as vision was explained “as the outcome of the formation of an image in the eye due to light” (Russell, 1996). Here is a description from his “Optics”:

> “The experimenter should then gently move the strip [**with a word written on it**] along the transverse line in the board, making sure that its orientation remains the same, and, as he does this, direct his gaze at the middle strip while closely contemplating the two strips. He will find that as the moving strip gets farther from the middle, the word that is on it becomes less and less clear.... and decreases in clarity until [the observer] ceases to comprehend or ascertain its form. Then if he moves it further, he will find that the form of that word becomes **more confused and obscure**.” (Ibn al-Haytham, translated in Sabra, 1989, pp. 244–245, cit. after Wade, 1998; emphasis added).

Importantly, al-Haytham used words, not single letters, in the experiment. So the “confused and obscure” percept arises from crowding. The only ingredient that is missing for an experimental unveiling of crowding is a direct comparison with single letters at the same eccentric location, which he could have easily done with his apparatus.

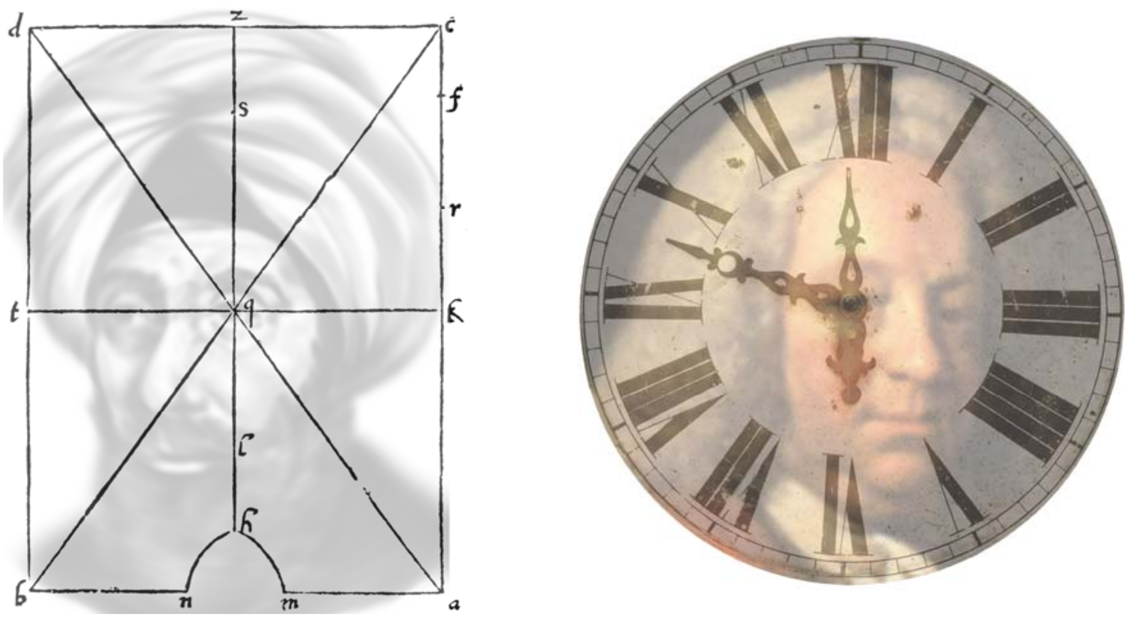

Figure 15. (a) Portrait of Ibn al-Haytham (c. 965 – c. 1040), with his perimeter superimposed (from Strasburger & Wade, 2015b). (b) Portrait of James Jurin (1684 – 1750) with a clock face, as described in his text and common at the time, superimposed. Note that the number Four is not in correct roman notation, so crowding will have been more prominent (from Strasburger & Wade, 2015a). Both artworks by Nicholas J. Wade (2015).

A second example for close misses is James Jurin’s *An essay on distinct and indistinct vision* (1738; Strasburger & Wade, 2015a):

> “The more compounded any object is, or the more parts it consists of, it will, ceteris paribus, be more difficult for the eye to perceive and distinguish its several parts.” (Jurin, 1738, p. 150)

There are two examples in his essay that are likely to have elicited crowding:

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> ''173. [. . .] For instance, it is somewhat difficult for the eye to judge how many figures are contained in the following numbers, 1111111111; 1000000000. But if we divide the figures in this manner, 11111,11111; 10000,00000; so as to constitute several objects less compounded, we can more easily estimate the number of figures contained in each of those numbers; and more easily still, if we thus divide them, 1,111,111,111; 1,000,000,000.'' (Jurin, 1738, p. 150)

A rough estimate shows that, at normal reading distance (30 cm), these patterns have around 4.5° extent and 0.5° centre-to-centre letter distance and are thus expected to undergo crowding. A second example in the treatise refers to a clock face:

> ''175. [. . .] For instance, the hour I. upon a dial plate may be seen at such a distance, as the hours II, III, IIII, are not to be distinguished at, especially if the observer be in motion," (Jurin, 1738, p. 151)

From the end of the latter quote (and what follows in the essay), Jurin is at a loss of explaining the phenomenon by ray tracing (as he does in all other of his many examples) and instead invokes self-motion for an explanation. Thus, even though Jurin comes close to discovering the phenomenon, through his very careful description of visual phenomena and his concept of *indistinct vision*, he finally stays with the contemporary way of analysis based on a blurred retinal image (cf. Strasburger, Bach, & Heinrich, 2018).

Conclusion

So should we care? Much of what I said above might be obvious. Or, on the other end of the spectrum, you might disagree with some points. The points made above are also not all equally important and not all of general interest. In any case, once a myth has found its way into a textbook, it is very hard to remove it for good (cf Wilkes, 1997). Not only that, it will also spread – like a virus, unfortunately. Textbook authors copy from other textbooks. Scientific authors copy from textbooks. Wikipedia excerpts from textbooks. Lecturers take their materials mostly from textbooks. We probably all know examples[5]. Thus, vision scientists better discuss the obvious in time, and weed out the shady parts and the fluff. I thus wish to invite my readers to a discussion and hope for many more articles on myths.

Acknowledgements

I would like to express my thanks to Nick Wade for a critical reading of the manuscript and pointing out more myths in neuroscience.

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[5] Is there a Weber-Fechner Law? Or is that a *textbook duck*? Which term is correct: "chi-squared" or "chi-square"?

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