Seven myths on crowding[1]

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Abstract

Crowding has become a hot topic in vision research and some fundamentals are now widely agreed upon. For the classical crowding task one would likely agree with the following statements. (1) Bouma's law can be succinctly stated as saying that critical distance for crowding is about half the target's eccentricity. (2) Crowding is predominantly a peripheral phenomenon. (3) Peripheral vision extends to at most 90° eccentricity. (4) Crowding increases strongly and linearly with eccentricity (as does the minimal angle of resolution, MAR). (5) Crowding is asymmetric as Bouma (1970) has shown. For that inner-outer asymmetry, the peripheral flanker has more effect. (6) Critical crowding distance corresponds to a constant cortical distance in primary visual areas like V1. (7) Except for Bouma's (1970) paper, crowding research mostly started in the 2000s. I propose the answer is 'not really' to these assertions. So should we care? I think we should, before we write the textbooks for the next generation.

Keywords: Crowding, Psychophysics, Perception, Reading, Visual acuity, Peripheral vision, Fovea, Asymmetries, Sensory systems, Cortical map, Vision science, Visual field.

Introduction

In 1962, the ophthalmologists James Stuart and Hermann Burian published a study on amblyopia where they adopted a nice and clear term, *crowding*, to describe why standard acuity test charts are mostly unsuitable for amblyopic subjects: On most standard charts, as ophthalmologists and optometrists knew, optotypes on a line are too closely spaced for valid assessment of acuity in all cases, such that in particular amblyopic subjects (and young children) may receive too low an acuity score. The phenomenon had been reported earlier by the Danish ophthalmologist Holger Ehlers[2] (Ehlers, 1936, 1953), who was perhaps the first to use the term *crowding* in that context, and it was treated in Adler's textbook (Adler, 1959, p. 661-662). Because amblyopic vision – commonly known as the "lazy eye syndrome" – leads to a strangely impaired percept and is quite unlike familiar blurred vision, it has, for the purpose of illustration, often been likened to peripheral (or indirect[3]) vision, which shares that obscureness (Strasburger & Wade, 2015a). Indeed the same phenomenon of crowding with closely spaced patterns occurs there, i.e. at a few degrees of visual angle away from where one fixates. A simple example is shown in Figure 1. Note that the visibility is not a matter of the target size

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

[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."

[3] *Indirect vision* in a term describing vision off the point of fixation. It is often used synonymously with *peripheral vision* but has a different emphasis (seeing off-centre). See the appendix in Strasburger (2014) for a discussion of these terms.

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here, i.e. has nothing to do with acuity or resolution in the visual field. Note further that standard textbook theories based on local, bottom-up processing, invoking simple vs. complex receptive field types, retinal lateral inhibition, rate of convergence/divergence of sensory neurons and the like, will not explain the phenomenon which, as we today know, happens in the cortex (for discussions of theories see, e.g., Tyler & Likova, 2007; Pelli, 2008; Strasburger, 2014; Kwon, Bao, Millin, & Tjan, 2014; Rosenholtz, 2015; Strasburger, 2019). Simple as it is, this little demonstration already shows that we have a very basic, general phenomenon of visual perception here, not some niche interest of vision researchers.

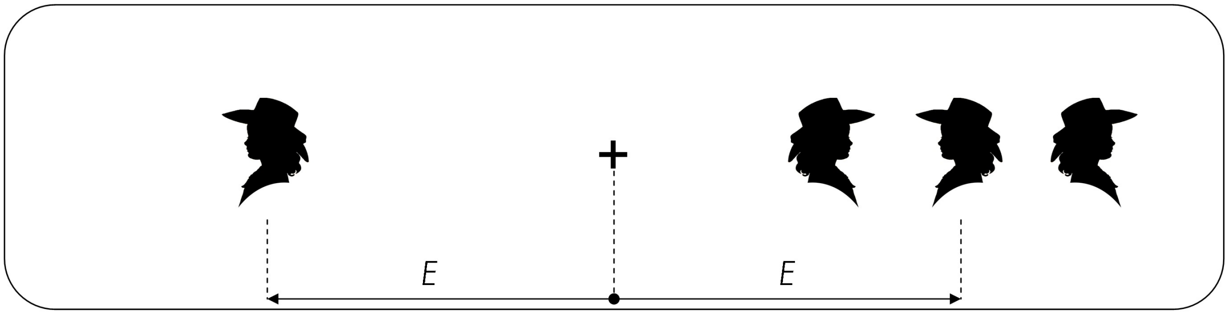

Figure 1. Simple demonstration of crowding. When fixating at the cross, the orientation for the hat on the left is seen but not that for the middle one on the right, even though the images are of the same size and at the same eccentricity. The phenomenon depends predominantly on eccentricity and pattern spacing and is mostly independent of target size.

Independently, and at around the same time, the phenomenon and related phenomena were studied quite extensively in a separate research tradition, Gestalt psychology (Korte, 1923) and later in experimental psychology (e.g. Wolford, 1975; Krumhansl & Thomas, 1977; Chastain, 1982; Chastain, 1983). Little did the schools of thought appear to know of each other: By the time that I became interested in crowding (1988), there were twenty major papers on the subject, under a variety of keywords[4] that, more often than not, took scarce notice of those of the other school (as evidenced by their references). Oddly, vision research – which, as the highly interdisciplinary field that it is, could have been the unifying ground – with a few exceptions appeared not interested. Neither were the cognitive sciences or visual neuroscience (and as it seemed to me at the time everybody else).

Things changed in the nineties and early 2000s. Dennis Levi had studied crowding in vernier acuity (Levi, Klein, & Aitsebaomo, 1985a); Lew Harvey suggested that we (myself, Ingo Rentschler and Lew Harvey) study character crowding at low contrast and ask what mechanisms might underlie crowding (Strasburger et al., 1991; Strasburger & Rentschler, 1995). He et al. (1996) pointed to the role of spatial attention and, in particular, Denis Pelli started projects on crowding and published a seminal 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, and that it overrides the latter even in foveal vision, widely held to be superior *because* of its outstanding acuity (Pelli et al., 2007; Pelli

[4] E.g. *lateral masking, lateral inhibition, lateral interference, interaction effects, contour interaction, surround suppression* (cf. Strasburger, Harvey, & Rentschler, 1991).

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& 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 two core assumptions in visual perception (cf. Strasburger & Wade, 2015a), namely that good vision comes down to good acuity, and, more generally, that a reductionist approach is always and necessarily 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 standard for covering all the senses is Goldstein's well-known *Sensation and Perception*. Acuity, receptive fields, cortical magnification, and peripheral vision are all covered – yet it says nothing about crowding. Even more worrying, acuity and crowding are confused as shown below in Figure 2 (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 explanation does not transfer to the several German editions which were edited by expert vision scientists (see Figure 2). Another standard, *Basic Vision* by Snowden, Thompson & Troscianko, a more recent (and enjoyable) perception textbook for the visual modality, explains cortical magnification and shows Anstis's visual demonstration of that in its first edition (2006), but also skips crowding. The same is the case in the new, 2nd edition (2012). The section on peripheral vision (pp. 117–119) shows a modified version of Anstis's magnification chart and explains scaling and cortical magnification (the chart is the impressive but misleading version of Figure 9b discussed later here in the paper, with a caption[5] that warrants understanding why it is wrong).

[5] 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 (Levi, Klein, & Aitsebaomo, 1985b; see Strasburger, Rentschler, & Jüttner, 2011, Section 3.2, for review), but its definition is misunderstood. It is defined as a doubling of the *foveal* value, not a doubling *every* 2.5° as said in the caption. 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 Misconception 3), so is scaled 10-fold as steep as required for legibility.

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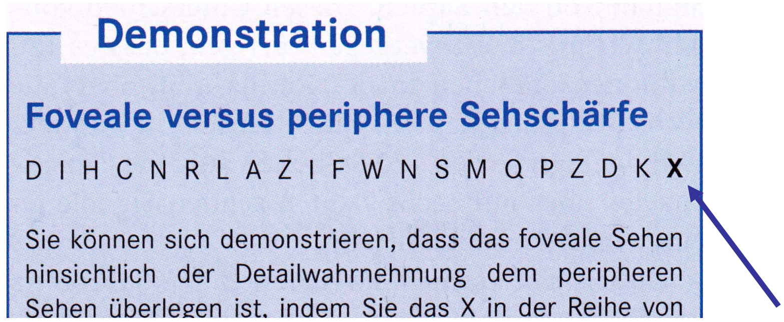
Demonstration

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 2. 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. The accompanying text reads, "You can demonstrate to yourself that, with respect to perceiving detail, foveal vision is superior to peripheral vision by fixating the X …". The added arrow shows where to fixate.

Thus, either crowding is after all much less important for vision in general than those who work on that subject 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, the workshops[6], theses, and in short the observation that crowding is nowadays a kind of 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 spread. 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 beliefs that, upon more scrutiny, turn out to be misleading or perhaps just wrong. The selection is entirely subjective; the points are a way of summarizing my unease while reviewing papers on crowding.

Note that, for now, the following is mostly about the isolated, "standard" crowding task – a target with singly occurring flankers – not about crowding, and crowding theories, in general. There will thus be further issues that might qualify as a 'myths', like the hope that two mechanisms might eventually explain crowding (many authors including myself invoke two mechanisms; they are just rarely the same). I simply stopped after seven points. The paper is the fifth in a series of – slightly pointed – "*myths"* presentations in vision research that I am aware of (Rosenholtz, 2016; Strasburger, 2017b; Bach, 2017; Strasburger, 2017a; Strasburger, 2018, *Preprint)*, and I trust more will follow[7].

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 3).

[6] E.g. Herzog, M. & Sayim, B. (2019). Workshop on Visual Crowding; June 23 – 24, Murten, Switzerland.
[7] On the more general subject of myths in neuroscience and what they have to do with occult passions, one will enjoy *The frog's dancing master* by Piccolino & Wade (2013). Or about the myth that the high iron content in spinach originated from a misplaced comma, you will be surprised to learn that that itself is a myth (Rekdal, 2014).

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Figure 3. Example of a German wimmelbild (Caro Wedekind, about the 31st Chaos Communication Congress (31C3) in Hamburg; Wedekind, 2014). Pictures like this show that visual search and crowding are connected subjects.

In medias res – one would agree with the following seven statements – or wouldn't one?

On Bouma's law

Misconception 1). Bouma's law can be succinctly summarized as saying that 'critical distance for crowding is about half the target's eccentricity (Bouma, 1970)'.

In a sense that is of course correct: Bouma's law is based on an experiment on letter triplets described in a Nature paper by Bouma (1970); it governs how crowding depends on the flankers' distance to the target and specifies the minimum distance for the interference as being approximately half the eccentricity value. However, the simplicity of the above statement's phrasing and the attribution are deceptive and give rise to a number of misunderstandings. Three of these I wish to address here: (1) generality and the role of Gestalt mechanisms; (2) whether critical distance can be seen as a *critical window*, and (as the main point here) (3) the role of a constant term and what constitutes a law.

On the first point, Bouma's finding turned out amazingly robust and general in describing a large variety of basic crowding situations; it works with letters, numerals, Landolt rings and many other patterns, and amidst many kinds of flankers in various numbers and orientations. It further tells us a lot about recognition of more complex patterns. After its first confirmation (Strasburger et al., 1991), Pelli, Palomares & Majaj (2004) have first studied a wide range of conditions. A few years later, Pelli & Tillman (2008) and Pelli (2008) discussed findings on its generality for proposing to raise Bouma's (1970) rule-of-thumb[8] to the rank of a law. Yet in spite

[8] "For a stimulus at φ° eccentricity, an open distance of roughly 0.5 φ° is required for complete isolation." (Bouma, 1970, p. 177)

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of that impressive range of applicability, it needs to be remembered that Bouma's law is *not* a descriptor for crowding in general. The reason for that is that human pattern recognition, for which the crowding phenomenon is a central ingredient, is first and foremost subject to Gestalt mechanisms (it is worth re-reading Korte, 1923, to remind oneself of the phenomenology). Gestalt mechanisms typically override the specifics of local stimulus configurations, obeying the simple truth that the whole is generally more than the sum of its parts. So as indicated above, the proven and tested concept of simplifying by analytical dissection can lead astray, in particular for the case of crowding, and the isolated crowding stimulus configurations like the ones in Figure 1 or Figure 4A do not predict target recognition when embedded in a larger surround. A typical Gestalt mechanism is *grouping*, by which the interference of the flankers in crowding can be eliminated or even inversed by adding a background with which those flankers group. This has been shown first by Banks, Larsson & Prinzmetal (1979, Fig. 5), and Wolford & Chambers (1983, Fig. 1) (see Herzog & Manassi, 2015, Fig. 2A, and Strasburger et al., 2011, Fig. 19, respectively). More recently it has been explored systematically in Bonneh & Sagi (1999), Livne & Sagi (2007, 2010), Levi & Carney (2009), and in a series of studies by Michael Herzog's group (Malania, Herzog, & Westheimer, 2007; Saarela, Sayim, Westheimer, & Herzog, 2009; Manassi, Sayim, & Herzog, 2012; Manassi, Sayim, & Herzog, 2013; Herzog, Sayim, Chicherov, & Manassi, 2015; see Herzog & Manassi, 2015, for review). Their message can be summarized as saying that "appearance (i.e., how stimuli look) is a good predictor for crowding" (Herzog et al., 2015). Chakravarthi & Pelli (2011) give that view a twist in saying it's not grouping among flankers that reduces crowding but, instead, that crowding is mediated by grouping of the flankers with the target (and is unaffected by grouping of the flankers with each other).

That said, this does not mean that, when grouping is involved, the distance between target and flankers no longer matters. All things equal, larger distance still means less crowding. The dependence on distance is changed, however, and in complicated ways that are not yet understood. Thus, grouping does not invalidate Bouma's law; it rather challenges us clarifying how Gestalt mechanisms interact with the local situation and thereby modify Bouma's law.

A second point in case concerns the influence of flankers further away than the critical distance and is related to the concept of a *crowding window*, introduced by Pelli in 2008 (Pelli, 2008; Pelli & Tillman, 2008). The proposed concept of a crowding window implies that crowding would occur *only* below the critical distance. Indeed, Pelli et al. (2004, p. 1146) suggested earlier that additional flankers surrounding the standard task have little or no influence. They point out, however, that the data of Strasburger et al. (1991) contradict that assumption. Herzog & Manassi (2015), in that context, phrase "Bouma (1970) showed that […] flankers interfere only when presented within a critical window […] (Bouma's law)". That can be read in two ways: as talking about Bouma's original two-flanker task (for which it would be correct) (the qualifier *only* would then refer to the tested flanker distances), or as ruling-out influences from outside the window (where the *only* refers to the closest vs other flankers). However, Herzog et al. (2015, p. 1) phrase the assertion explicitly as "Crowding is determined only by nearby elements within a restricted region around the target (Bouma's law)." Both papers continue to show that the assertion of no influence from outside the window is incorrect and might thus be taken as disproving Bouma's law (Strasburger et al., 1991, had already shown that four flankers exert more influence than two, i.e. that the assertion of no influence from outside is incorrect). Now, given that Bouma himself never talked about a multiple-flanker crowding situation, and further

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that the evidence is clearly against a “nearest-only” assertion, it would seem that this assertion should not be made a constituent for a law in Bouma’s name. We thus need to pay close attention to the law’s precise phrasing and to the referenced attribution.

As to the idea of a crowding window where only the nearest neighbour counts, another interesting example for why the exact wording of Bouma’s rule (or law) matters is the paper by Van der Burg et al. (2017, p. 690) on the applicability of Bouma’s rule in large, cluttered displays. The paper’s conclusion is “that Bouma’s rule does not necessarily hold in densely cluttered displays [and] instead, a nearest-neighbour segmentation rule provides a better account.” On the surface this might be taken as saying that equation (1) or (2) do not hold when displays are complex. But this is not at all what is meant. What is meant is simply that the half-eccentricity rule was not met at the tested eccentricity (and a counterexample disproves a rule). Only a single eccentricity was tested (since the paper’s goal was elsewhere), so linearity or the dependence on eccentricity were not at stake. The results would be compatible, e.g., with Bouma’s rule as stated, e.g., in Pelli et al. (2004), just with a much smaller slope factor. So again, when a rule is *disproven* it is imperative to behold the precise phrasing that is referred to (in this case the original rule).

As to the third point, what follows here in the paper is about the isolated crowding task. For that, the statement in the header sounds sensible enough and suffices as a rule-of-thumb, as originally intended. We can do better, however. The amazing robustness and generality across configurations of that rule suggests there is something much more fundamental about it. Starting with Pelli (2008), authors now tend to call it a law rather than a mere rule, equal in rank to other laws of psychophysics like Weber’s law, Riccò’s law, Bloch’s law, etc. Now the requirements for a law as, e.g., standardly applied in classical physics are higher. One requirement is *generality*, but this is obviously a given, at least for the isolated crowding task. Another requirement, however, concerns the mathematical formulation. Not only should the mathematical description of a real-world dependency fit the empirical data, it must crucially also fulfil certain a-priori, theoretical constraints: namely to make sense for the obvious cases. I.e. it must obey *boundary conditions*. As a trivial example, in the equation specifying the distance of the earth to the moon in the elliptical orbit, that distance may vary but it must not be negative, and better not be zero. Or, for Weber’s law, zero intensity must be excluded for the principled reason that Weber’s ratio is undefined there (and the law further breaks down near the absolute threshold as explained by a statistical model by Barlow, 1957). Riccò’s law must be constrained to the area in which energy summation takes place. Lack of such constraints is where the mathematical formulation in the header fails.

To get to that point, let us consider the qualifier *about* in the header statement. Mostly it is understood as referring to the factor 0.5 in Bouma’s 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, sometimes more (0.13 and 0.7 in Strasburger & Malania, 2013, eq. 5 and 6). However, *linearity* holds amazingly well for almost all visual tasks. So that ambiguity about the factor can be easily accommodated by replacing the fixed slope factor of 0.5 in the equation by a parameter that depends on the

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particular task in question.

There is a more important slur, however, a limitation of the rule's generality in range. This becomes apparent when considering the particularly important case for crowding: foveal vision and reading. The eccentricity angles (φ) in question are small there and thus the precise meaning of a critical distance becomes important (Figure 4). Bouma (1970) specified *d* as the threshold of internal or empty space between target and flankers; today's authors mostly prefer to specify flanker distance as measured centre-to-centre, since critical spacing then remains mostly constant across sizes as has often been shown (Tripathy & Cavanagh, 2002; Pelli et al., 2004; Pelli & Tillman, 2008; Levi & Carney, 2009; Coates & Levi, 2014; c.f. also van den Berg, Roerdink, & Cornelissen, 2007, even though the independence is not perfect, e.g. Gurnsey, Roddy, & Chanab, 2011).

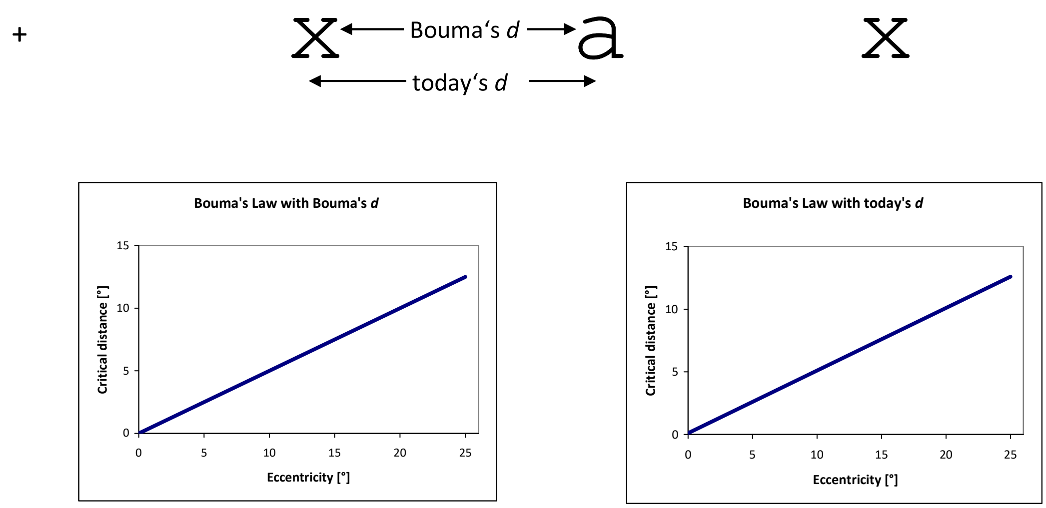

Figure 4. Top: Bouma's crowding stimulus arrangement. On the left is a fixation point (+), to the right of which a target letter ('a') appears that is surrounded by two equally-spaced flankers ('x'). Target and flankers are in Times-Roman font, with a variable number of fixed-width spaces in between. 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 but is seen when zooming-in on the manuscript (about 10-fold; inspect the origin) (or see the next figure).

At small eccentricities, where (by Bouma's rule) flankers at the critical distance are close to the target, that difference of specification matters (Figure 5). With Bouma's empty-space definition, critical distance is *proportional* to eccentricity (pink line in Figure 5a). With the 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 5a, where the blue line is shifted vertically 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 meaningless in the fovea centre: 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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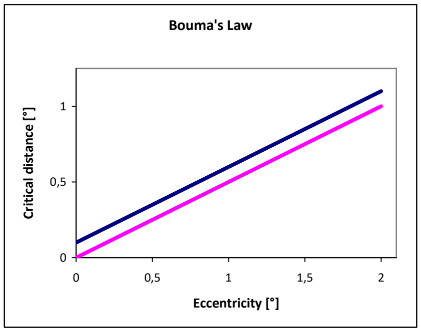

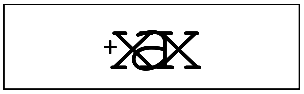

Figure 5. (a) Comparison of Bouma's law with critical distance defined as empty space (pink) vs. centre-to-centre (blue). (b) A degenerated stimulus configuration that would result from an incorrect statement of Bouma's law at small eccentricity.

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

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

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.

Yet perhaps equation (1) is just more elegant and appealing? Note then that equation (2) is formally equivalent to *M*-scaling (i.e. compensating for the differing cortical neural machinery across the visual field). Isn't that beautiful? It has ramifications of its own that we wrote about elsewhere (Strasburger & Malania, 2013; Strasburger, 2019) (for a review of M-scaling see Strasburger et al., 2011, Section 3, and eq. 9 below). We will get back to that when we speak about the cortical map.

In summary, if taken as a rule-of-thumb as intended by Bouma, the statement in the header is fine and only needs to be qualified as referring to empty space; its attribution to Bouma (1970) is correct. However, once we speak of a law, more care is needed. There is probably agreement that there is something very profound to Bouma's rule and that we are on our way to formulating a law – Bouma's law – similar to other classical laws of psychophysics. It still needs to be sorted out though what its essence is. Is it the specific factor (0.5, or perhaps 0.4)? Is it the linearity, irrespective of the factor? Can it be generalised beyond the isolated task, and how? Furthermore, the attributions need to be explicit because different authors put the emphasis differently. An attribution of the law to Bouma (1970) without further pointers, in any case, would be incorrect and can be misleading. Importantly, the precise phrasing is particularly important when the rule or law is said to be disproven rather than validated.

Crowding and peripheral vision

Misconception 2). Crowding is predominantly a peripheral phenomenon.

Crowding is of course highly important in the visual periphery. It is often even said to be *the* characteristic of peripheral vision (for example 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. 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

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that the fovea is much larger than one is mostly aware of: its diameter is around 5.2 deg visual angle (Polyak, 1941; Wandell, 1995). Note in that context that ophthalmologists appear to use the terms differently, referring to the 5.2° area as the macula lutea even though the anatomical macula is again larger (estimated at 17° diameter by Polyak.) Another source of confusion is the use of the term 'foveal vision'. When vision scientists use that term or speak of 'the fovea', they are typically not referring to the foveal area but are talking about the situation where the observer fixates; i.e., they effectively refer to the foveola (about 1.4° diameter) or indeed to the point of highest receptor density, the very centre. That maximum is reached in an area of only about 8–16 arcmin diameter (Li, Tiruveedhula, & Roorda, 2010, Fig. 6[9]); the point of fixation (i.e. the preferred retinal locus; PRL) is furthermore not there but is between 0 and 15 arcmin away from that point (Li et al., 2010, Table 2). As a practical example, when an optometrist or ophthalmologist measures visual acuity, the result likely refers to the short moment when the gap of the Landolt ring is at the PRL, i.e. several arcmin away from the fovea's centre. It is then that maximum acuity is achieved and in young adults about half a minute of arc is resolved.

In the rest of the fovea, acuity as we all know is much lower. Phrased a bit offhand, 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 not only present off-centre (i.e. for indirect vision) but is also present in the very centre. That has been controversial for a time but appears now well established (Flom, Weymouth, & Kahneman, 1963; Levi et al., 1985a; Levi, Klein, & Hariharan, 2002b; Coates & Levi, 2014; Siderov, Waugh, & Bedell, 2014; Coates, Levi, Touch, & Sabesan, 2018; see Coates & Levi, 2014, for review up to 2014). There is agreement that the interaction effect of foveal acuity targets, measured with conventional techniques, occurs "within a fixed angular zone of a few min arc" (3'–6') (Siderov, Waugh, & Bedell, 2013; Siderov et al., 2014, p. 147). However, a new study using adaptive optics (Coates et al., 2018) shows critical spacings are indeed even much smaller and only about a quarter of that range, 0.75 to 1.3 arcminutes edge-to-edge.

Whether the lateral interactions in the centre should be called 'crowding' is another question. Its characteristics might (or might not) be different from those further out. Levi et al. (2002b) have it in the title – "Foveal crowding is simple contrast masking". 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 et al., 2004), that seems less so to be 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 6a). Coates & Levi (2014) call that behaviour the *hockey stick model*. Yet the new adaptive-optics data show that, for small sizes and if suitably extracted, "edge-to-edge critical spacings are exactly the same across sizes" (Coates et al., 2018, Fig. 2). It thus seems that even

[9] For conversion: 3.43 deg/mm (cf. Le Grand, 1957, p. 50)

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in the very centre we might have standard crowding[10].

Let us consider for a moment how the 2014 hockey stick model is related to Bouma's law. The hockey stick model describes the situation at a single location, 0° eccentricity. For a target there of up to 5' size, centre-centre critical spacing is a constant 5' (Figure 6a). The stimuli in Siderov et al. (2013) are Sloan letters surrounded by bars (having the same stroke width), so the statement could be rephrased as saying that, for Sloan letters below 5' size presented at the very centre, the bars' midline must not be located nearer than at 5' eccentricity to not crowd. Yet that statement appears to me as rephrasing the independence of target size in the centre, up to 5' size.

Above 5' letter size, critical spacing is proportional to target size according to the hockey stick model. Now note that, by definition, that spacing is adjacent to the target, and, with increasing target size, its centreward border will move outward at a rate of half the target size (because the target is centred at 0° and extends by s/2 to one side). Thus, when *s* exceeds 5' and the critical gap *g* is smallest (at 1')[11], it "pushes" the flanking bar outwards. The rate at which that happens is equal to size *s,* telling from the 45°slope of the hockey stick. Gap size g, by the same argument, can be shown to follow $g = 0.3\, s - 1'$ (for s>5').

Taken together, the hockey stick model appears compatible with the independence of target size at 0° eccentricity (up to 5' size), and roughly with Bouma's law at 0° in that gap size is small (>1') but not negative. Phrased simply, targets at 0° just need to be small enough that they do not come closer than 1' to an edge at 3.5'.

The question remains as to what Bouma's law looks like at very small eccentricities, just off the centre. To recapitulate, at 0° critical gap size is about[12] 1'–3.7' ("old" model in Figure 6a) (or 0.75'–1.3' c-c according to the new, adaptive-optics data). Now does critical gap size, with increasing target eccentricity, increase linearly from there or does it first behave differently for a few minutes of arc, and then increase (Figure 6b)? The hockey stick model, though speaking only about 0° eccentricity, appears to suggest the *latter*: By the same thought experiment as above, a target that is just off centre has its boundary just a little more outward, like a target at 0° that is a little larger. The nearest flanker is expected to be still at 4', so that critical gap size might even decrease a little at first, until the target boundary comes closer than 1', at which point standard Bouma's law kicks in.

As a corollary, that would imply that Bouma's law with the empty-space definition is not strictly proportionality after all, but has some other behaviour below perhaps 4' (Figure 6b). A direct test of Bouma's law at very small eccentricities (0 – 0.2°), together with how it fits in with size dependency, will thus be interesting.

[10] Coates et al. (2018) also isolate a separate recovery mechanism, first observed by Flom et al., 1963, at even smaller distances – 0.5–0.75 arcminutes – that can be left aside for the present discussion.
[11] The kink in the hockey stick is at *s*=5'. The bar is at 4' eccentricity; it has the same stroke width as the letter, *s*/5=1'. The gap thus extends from 2.5' to (4'–0.5'), i.e. is 1' wide.
[12] Calculated for a 0.5' target and a 5' target, with the bar at 4' as in Figure 6a

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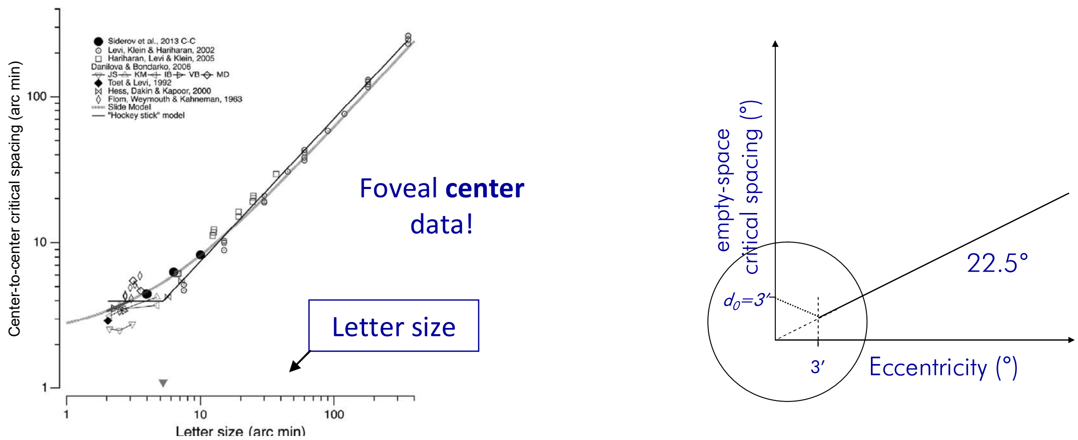

Figure 6. (a) Coates & Levi's (2014, Fig. 4, annotated), illustrating their 'hockey stick model' that describes the dependence of centre-to-centre critical spacing on target size. The filled circles show Siderov et al.'s (2013) data for Sloan letters surrounded by bars. Note that the slope is ≈1.0, i.e. an increase of letter size leads to an increase of c-c CS by the same amount. The figure is annotated to emphasize that the abscissa is different from the previous figures and no eccentric data are shown. (b) Possible shapes of Bouma's law in the visual field's very centre (with a slope of 0.5 = 22.5°) that would be compatible with the hockey-stick model.

In summary, crowding is not just a peripheral phenomenon. It is present, and in a sense even more important, in the foveal area. Also beware that saying "in foveal vision" would likely mean something else.

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 peripheral visual field refers to the area from 30° eccentricity outwards. Within that 30° radius, the area is referred to as the "central visual field". The periphery in that sense is several times the central field in area. It extends, on the temporal side, to around 107° eccentricity (Rönne, 1915; Traquair, 1938). Note in that context: Not to 90° as stated in many or most modern textbooks. But that is another myth story (Strasburger, 2017b; Bach, 2017).

Size of the visual field

Misconception 3). Peripheral vision extends to at most 90° eccentricity.

This myth is not directly on crowding; but since it is relevant to crowding, we briefly touch upon it here.

An obvious way of finding out the size of the healthy visual field would appear consulting a standard textbook on perimetry and inspect the outermost isopter (line of equal differential luminance/contrast sensitivity) for the normal visual field. It is largest on the temporal side and extends to about 90° eccentricity. Intuitively that also seems to make sense: Light from a point in the visual field reaches the corresponding point on the retina approximately in a straight line (from the nodal points the external and internal eccentricity angles are the same), so rays reaching the eye tangentially would not enter the eye.

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Both assertions are, of course, wrong; the first hinges on the definition of the normal visual field; the second only works for rays entering from directly in front of the eye. The misunderstanding for the first assertion is that the outermost line represents the maximum extent of the healthy visual field, when in fact it only shows the maximum extent for the specific stimuli used in the respective perimeter. When perimeters were developed for routine use in a clinical environment, standardisation was a prime requirement. Since the diagnostic aim is finding impairments that warrant medical intervention, stimuli were chosen to be relatively weak to allow for sensitive testing[13]. Furthermore, the automated cupola perimeters were, presumably to preserve space but also due to the mechanical, projection-related limitations of the stimulus excursion, designed such that the maximum angle to the side was limited to 90° eccentricity (some models had optional additional panels on the side to extend the horizontal range of measurement). However, what was forgotten over time, it seems, was that with higher-contrast stimuli the visual field would extend quite a bit further out on the temporal side. The anatomical factors responsible for the visual field's outer limits (eye brows, eye lashes, orbital bones) allow for the maximum extent in the temporal region, exceeding 90 deg. Figure 7 shows the classic visual field diagram drawn by Harry Moss Traquair in his book on clinical perimetry (Traquair, 1938), using data reported by Rönne (1915). Only just recently, there are again maps that go beyond 90° eccentricity (Figure 7b).

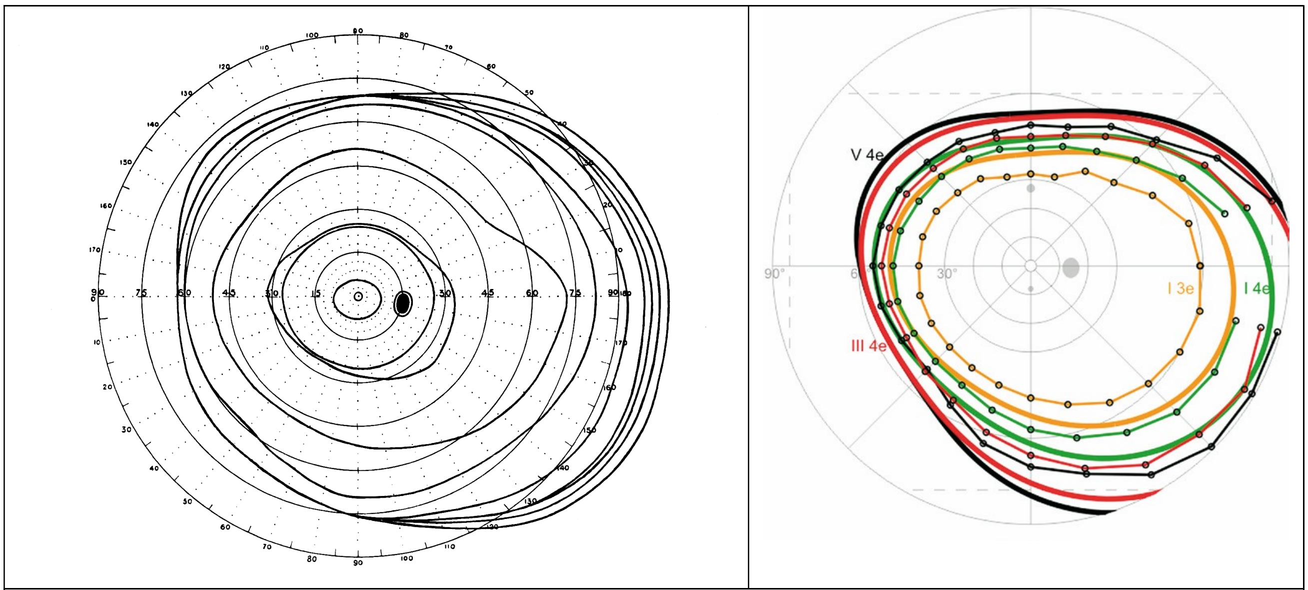

Figure 7. (a) The visual field, as drawn by Traquair (1938, Fig. 1) in his classical book, based on the data by Rönne (1915). The outermost contour is for a stimulus of 160 mm diameter, presented at 1 m viewing distance, i.e. of 9° size. (b) A recent visual field map obtained with reaction-time-corrected, semiautomated kinetic perimetry (Vonthein et al., 2007, Fig. 3a).

[13] Yet contrary to the underlying assumption, the so-called *temporal crescent* (starting at an eccentricity of approx. 50° and extending to more than 90°) is indeed of neuro-ophthalmological importance: Losses in that area indicate the affection of post-chiasmal fibers, emanating from the contralateral peripheral nasal retina. Typical locations are the contralateral Meyer's loop or the contralateral deep-rostral portion of the striate cortex (U. Schiefer, personal communication, July 2019).

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That the visual field extends to more than 90° on the temporal side has long been known. Purkinje (1825) found it to extend temporally up to 115°:

> "My measurements of the width of indirect vision indicate a temporal angle of 100 degrees (extended to 115 degrees when the pupil is enlarged by Belladonna), 80 degrees downwards, 60 degrees upwards, and the same value for the nasal angle" (Purkinje, 1825, p. 6; cited after Wade, 1998, p. 342)

Alexander Friedrich von Hueck, professor of anatomy in Dorpat/Livonia (now Tartu/Estonia; see Simonsza & Wade, 2018, for a portrait), wrote in 1840,

> "Outwards from the line of sight I found an extent of 110°, inwards only 70°, downwards 95°, upwards 85°. When looking into the distance we thus overlook 220° of the horizon." (Hueck, 1840, p. 84, translated by HS)

This is already a precise description of the visual field's outer limits that is valid today. Rönne's (1915) data were thus not surprising but provided a firm ground for Traquair's (1938) famous map which made the visual field's shape and size explicit (reproduced, e.g., in Duke-Elder, 1962, p. 411). For the schematic eye, Le Grand (1957, p. 51, 52) later derives "an angle of about 109° on the temporal side". Mütze (1961), a standard German optometry book, shows isopters that go far beyond 90°. Similarly, Trendelenburg (1961) states as the temporal extent 90° – 100°, referring to Hermann Aubert. Schober (Schober, 1970) states 90° – 110° and also points to the fact that the maximum temporal extent is not reached on the horizontal meridian but about 25° downwards (which can also be seen in Traquair's graph) (the last three references provided by B. Lingelbach, July 2017). Anderson (1987) shows a visual field that goes to 100° and has a slightly different shape (Simpson, 2017, Fig. 5b). Wade and Swanston (1991, Fig. 3.4, p. 36) give as the maximum extent 104°. Wandell's (1995) "Foundations of Vision" (which has a widely-used collection of useful numbers for vision research in the inner cover) gives an overall combined angle of 200°, i.e. ±100° to the temporal side. One can verify for oneself that the maximum angle is more than 90° by simply wiggling a finger on the side, from slightly behind the eye. Personally, I became aware of a possible conflict by a question from Ian Howard at VSS 2003 on my new book on peripheral vision (which I presented there and in which I claimed the extent to be 90°), when Ian Howard was about to (correctly) state 110° in his upcoming 2nd volume of his book. Indeed, however – perhaps after our conversation – he finally (incorrectly) stated 93° (in Fig. 14.1: 114°/2+36°), or "about 95°" in the text, citing Fischer & Wagenaar (1954, p. 370, who in turn cite Fischer, 1924 for these numbers) (Howard & Rogers, 2012, Vol. 2, p. 149).

Thus, by the middle of the 20th century, the maximum extent of the visual field being markedly beyond ±90° was well-established textbook knowledge. It is all the more surprising that this knowledge appeared suddenly lost, or perhaps considered irrelevant, at some point. The well-established German textbook on ophthalmology, Axenfeld & Pau (1992, p. 52), e.g., states in its 13th edition (translated), "A normal monocular visual field extends temporally to about 90°, nasally and upwards to 60°, downwards to 70°." Lachenmayr & Vivell's (1992, p. 3) book on perimetry does not state the normal extent but instead shows normal maps that go to 90°. Sekuler & Blake (1994, p. 114, 115) write, more precisely, "A normal visual field map for each eye looks like the pair numbered 1 in the accompanying figure". The accompanying figure shows two perimetric maps that go to 90°. This is of course correct. Yet maps like these are likely

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misunderstood as showing the extent of the whole field. Indeed, Karnath & Thier's standard German textbook on neuropsychology (2006, p. 92) writes on the visual field (translated), "The section that we can see simultaneously without moving our head or eyes is quite large; under binocular conditions it extends to about 180° horizontally and 100° vertically". Similarly, Diepes, Krause & Rohrschneider (2007) say (translated), "1.1.2 Visual Field. The healthy visual field typically extends to about 90° temporally, 60° nasally, 50° downwards and 40° upwards. Note these extents are, to a certain degree, dependent on the respective stimuli used" (the last sentence might hint at the field being larger with stronger stimuli). Surprisingly, many textbooks on vision do not mention the size of the visual field at all, even though one would think this is basic knowledge on vision (see Table 1 for a summary; further details summarized in Strasburger, 2017c and Bach, 2017).

Study	**Temporal extent**
Purkinje (1825)	115°
Hueck (1840)	110°
Rönne (1915)	107°
Traquair (1938)	107°
Fischer & Wagenaar (1954)	(94°)
Le Grand (1957)	109°
Mütze (1961)	(>> 90°)
Trendelenburg (1961)	100°
Duke-Elder (1962)	(107°)
Aulhorn (1964)	(90°)
Schober (1970)	110°
Pöppel & Harvey (1973)	(90°)
Anderson (1987)	(100°)
Wade & Swanston (1991)	104°
Wandell (1995)	100°
Axenfeld & Pau (1992)	90°
Lachenmayr & Vivell (1992)	(90°)
Sekuler & Blake (1994)	(90°)
Karnath & Thier (2003)	90°
Howard (2002)	110°
Diepes, Krause & Rohrschneider (2007)	90°
Vonthein et. al. (2007)	(>> 90°)
Strasburger et al. (2011)	90°

Table 2. Books or studies, sorted by publication date, and visual field extent on the temporal horizontal meridian. Values in parentheses were not stated but are implicit in the graphs.

As to the second assertion, the rationale that light cannot enter from the side, the answer is simply that the cornea protrudes in the eyeball so that light from the side gets refracted enough to enter the pupil. Figure 8a shows a ray-trace model by Holladay & Simpson (2017). With both a 2.5-mm and 5-mm pupil, the model predicts a maximum horizontal angle of 109° eccentricity.

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Figure 8. (a) Ray-trace model of how light enters the eye at the maximum angle for a 5-mm pupil (Holladay & Simpson, 2017, Fig. 3a). (b) Pupil as seen from an angle of 80° on the temporal side (Mathur, Gehrmann, & Atchison, 2013, Fig. 5). (c) Aspect ratio of the pupil's shape as seen by an observer under different horizontal angles, with data from eight different studies in the literature (coloured symbols) (Mathur et al., 2013, Fig. 1).

A nice way to visualize the effect of refraction by the cornea is looking at the eye of somebody else from the side (Figure 8b). If it were not for the refractive power of the cornea, the pupil would not be seen at all (since it is *inside* the eye), and even if it were, its circular shape would appear as a narrow vertical slit. However, when seen from the side it appears as a vertical ellipse (Figure 8b). The maximum angle at which light can enter the eye can then be estimated from the aspect ratio of that ellipse (Figure 8c) which in that graph vanishes at around 107°.

In summary, the visual field extends to about 107° – 109° eccentricity on the temporal side of the visual field, as has been known since the 19th century. The myth that it ends at 90° is likely due to technical limitations of standard perimeters for widespread clinical use, and a misinterpretation of the resulting maps. It has spread to numerous textbooks since.

Rate of increase towards the periphery

Misconception 4a). Intuitively, acuity decreases severely with eccentricity and crowding increases even more steeply.

Textbooks typically characterize peripheral vision by emphasizing its decreased spatial resolution, and how that is the cause for a general inferiority of peripheral vision. Goldstein's *Sensation and Perception* (Goldstein, 2002, p. 57) explains,

> "Have you ever found it difficult to locate a friend's face in a crowd? […] The reason you need to scan the crowd was that to see enough detail to recognize a face you need to focus the image of the face on your fovea […] Only all-cone foveal vision has good **visual acuity** – the ability to see details." (p. 57)

Often, then, an illustration follows showing how vision is heavily blurred or degraded towards the periphery. Now, as we all know resolution does indeed decrease (or, conversely, the minimal angle of resolution MAR increases). Yet, perhaps surprisingly, that happens only moderately. The myth of a steep MAR 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 9). The actual enlargement of peripheral letter size to accommodate cortical magnification is shown in Anstis's Fig. 2 (Figure 9a). However, since the letters are approximately at the acuity limit in that chart

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and are thus hard to recognize, Anstis at the time enlarged the letters tenfold in his Fig. 3 (here Figure 9b), for better visibility. That chart looks more appealing and intuitive and it is the one typically chosen elsewhere for illustrations of how the periphery differs from “ordinary” (i.e. foveal) vision (e.g. Snowden, Thompson, & Troscianko, 2006, Fig. 4.23). Yet as Rosenholtz (2016) has pointed out in an enlightening paper, this size enlargement at the same time dramatically overemphasizes the peripheral performance decline. That is because sizes are enlarged but eccentricities are not. The overemphasis is by the same (whopping) factor of ten. The misunderstanding then arises because the chart is usually interpreted too literally (which Anstis probably never intended). It is a good example of how pictures can lead wildly astray.

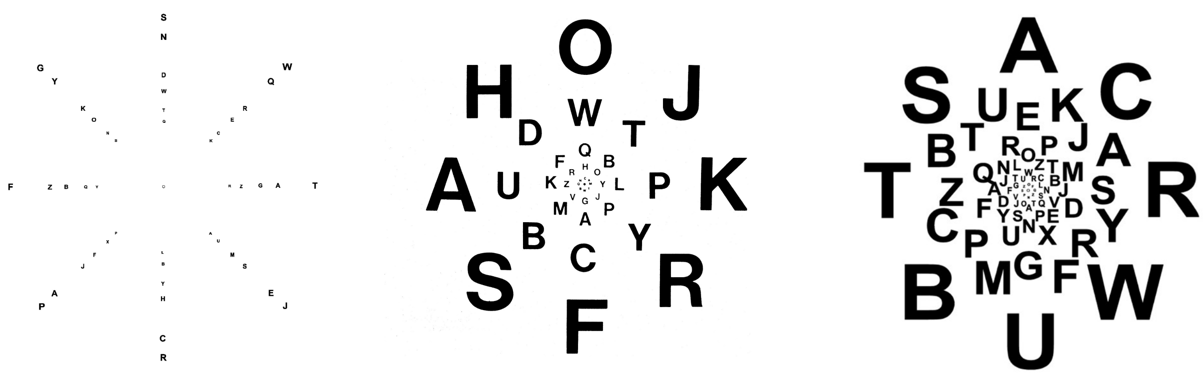


Figure 9. Figs. 2, 3, and 4 in Anstis (1974), illustrating cortical magnification. Letter sizes are according to an estimate of the cortical magnification factor (left). Letters are shown at a tenfold increased size (middle). Letter sizes are the same but more letters are added, to increase crowding (right).

But there is more. Anstis’s Fig. 3 (here Figure 9b) is intended to show single-character recognition, illustrating the increase of the MAR. The letter spacings, measured centre-to-centre, may appear adequately spacious for preventing crowding. Yet because, by design, letter sizes are not equal, it is empty space between letters from which the influence of crowding can be estimated. 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. That neighbour only leaves between 20% and 45% of φ space. There is thus, after all, quite a bit of crowding in that graph. Consequently, the alleged effect of MAR-increase in the chart is further overemphasized by inadvertent crowding.

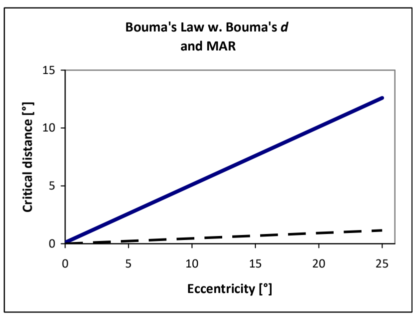
For a rough estimate of the actual rate of increase for the MAR, we can use the E_2 concept and peruse Table 4 in Strasburger et al. (2011) for an overview on the empirical range of rates.[14] Assume for that an E_2 value of 1° for Landolt acuity and a (decimal) acuity of 1.0 (“20/20”), i.e., a resolvable gap size of S_0 = 1’. These values imply a slope of 1’/1° or 1/60 = 0.017 deg/deg for the gap-size vs. eccentricity function (Strasburger et al., 2011, eq. 8). Alternatively, one can inspect the data for letter acuity shown in Anstis (1974). Fig. 1 in that paper, or the regression equation there[15], show a slope of 0.046 deg/deg for letter height. Since gap width is typically 1/5th of

[14] The E_2 value is the eccentricity increment for which the foveal value doubles, or, equivalently, for which the visual parameter in question increases by the foveal value (Levi et al., 1985b).
[15] Anstis’ regression equation can be simplified to $S = 0.046\ E$. As a caveat, note that that equation cannot be converted to an E_2 scheme and neither be described by *M*-scaling like in eq. (2). The reason is the difference

letter height, that translates to one-fifth of that slope (0.009 deg/deg) for the slope of MAR. In other words, we have a typical increase of roughly 1% − 2% for the MAR, which is very moderate indeed.

Anstis's third chart (Fig. 5, shown in Figure 9c) is an illustration of crowding. That chart is really crowded! Empty spaces are obviously far below the critical ½ φ. Letter sizes are the same as before, so we know acuity plays no role. Yet, again the demo chart needs some explanation. Crowding already took place in Figure 9b so already in that figure one probably could not recognize the letters with proper fixation. So no further effect of increased crowding will be seen. Furthermore, the large letters might lead one to believe that these sizes are what peripheral vision needs. One thus might wonder what, precisely, that last graph shows.

Now to the question how crowding increases with eccentricity. The increase of critical distance is certainly at a much steeper rate than it is for acuity: By Bouma's law, critical spacing increases at a rate of ½ deg/deg, which is *thirty times* the rate of increase for the MAR. It is much, much steeper. This is illustrated in Figure 10, which shows Bouma's law from Figure 4a together with the MAR (dashed line), from Anstis's paper (1974, Fig. 1).



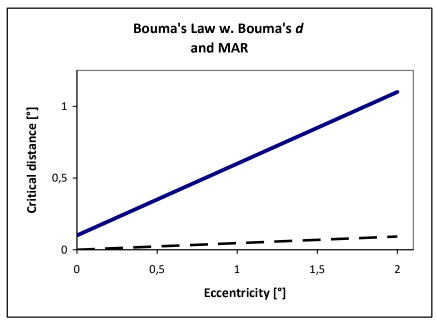


Figure 10. Bouma's law (continuous line, as in Figure 4a), compared to the increase of the MAR with eccentricity (dashed line; data from Anstis, 1974, Fig. 1). The graph is shown at two scales (as in Figure 4 vs. 5), to illustrate that at a large scale the slope difference matters most whereas at a small scale the intercept difference is more important.

Beware, however, that in a sense we are comparing apples to oranges here: for crowding, the measure is critical distance; target size does not matter much (Tripathy & Cavanagh, 2002[16]; Pelli & Tillman, 2008). For the MAR, in contrast, target size not only matters – it *is itself* the measure.

There is a further caveat for the intuition in the direct comparison between crowding and MAR shown in Figure 10, related to the cortical magnification concept: MAR is nicely described by cortical magnification (see Fig. 9 or Fig. 11 in Strasburger et al., 2011). Intuitively, one might thus think that the same comparison as in Figure 10 holds between crowding and cortical magnification. That, however, is not at all the case. The reason is that cortical magnification

between proportionality and a linear law, explained above (under M1); the linear law requires a non-zero foveal value (which in eq. 2 would translate to the constant term), which was not specified in Anstis's paper.

[16] "In peripheral vision [at an eccentricity of 9.2° in the lower visual field], a 5-fold change in target size produced less that a 15% change in the spatial extent of interaction". (Tripathy & Cavanagh, 2002, Fig. 4 and p. 2365).

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scaling is (by definition) a scaling concept, where the foveal value of a target's size is the reference, i.e., is the value that is scaled). The MAR line in Figure 10 is so shallow because the MAR's foveal value is really tiny (around 0.01°). If, however, in some experiment a medium-sized foveal target size is chosen (say 1°), the cortical-magnification-scaled results will be huge, and the slope can by far exceed the increase of crowding's critical distance.

In summary, the decrease of spatial resolution towards the visual periphery is rather modest and is generally overrated in its implications. Crowding is generally much more important as a limit to pattern recognition. Visualisations of decreased acuity in the visual periphery are often misleading, as are visualisations of crowding.

Misconception 4b). The extent of crowding increases linearly with eccentricity.

That statement sounds like repeating what was said above. Again the problem is one of careless phrasing, yet there is also something fundamental about that lapse. 'Extent' in English can refer to two rather different domains, *intensity* (magnitude), or *space*[17]. By its standard definition, the extent of crowding, or in short *crowding*, is understood as the *reduction of recognition performance* brought about by the presence of flankers. It is thus measured along a dimension that is different from the spatial dimension shown in Figure 10. For quantifying that extent, we need to convert *critical distance* to a measure of *recognition performance*.

To do that we require the psychometric function for letter recognition vs. flanker distance. A suitable performance measure is *percent correct* (p_c). Another well-suited performance measure would be *contrast threshold* or *threshold elevation*, which has greater dynamic range and avoids floor effects (Strasburger et al., 1991; Pelli et al., 2004; Strasburger, 2001b; Strasburger, 2001a; Strasburger, 2005; van den Berg et al., 2007, c.f. Fig. 8 there; Strasburger & Malania, 2013). For the present purpose though, we will stick with p_c. It is surprisingly difficult to find data for that in the crowding literature, even though it is basic for letter crowding. For the present purpose I chose data from Yeshurun & Rashal (2010, shown in Figure 11a, red line) that were collected as a baseline for a different research 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). Figure 11b and 11c show two further examples for the psychometric function vs. flanker distance from other labs (Rosen, Chakravarthi, & Pelli, 2014, Fig. 9a; Albonico, Martelli, Bricolo, Frasson, & Daini, 2018, Fig. 4).

[17] This is reflected in Fechner's classical distinction of *intensive* and *extensive* sensations (Fechner, 1860, Chpt. IV, p. 15).

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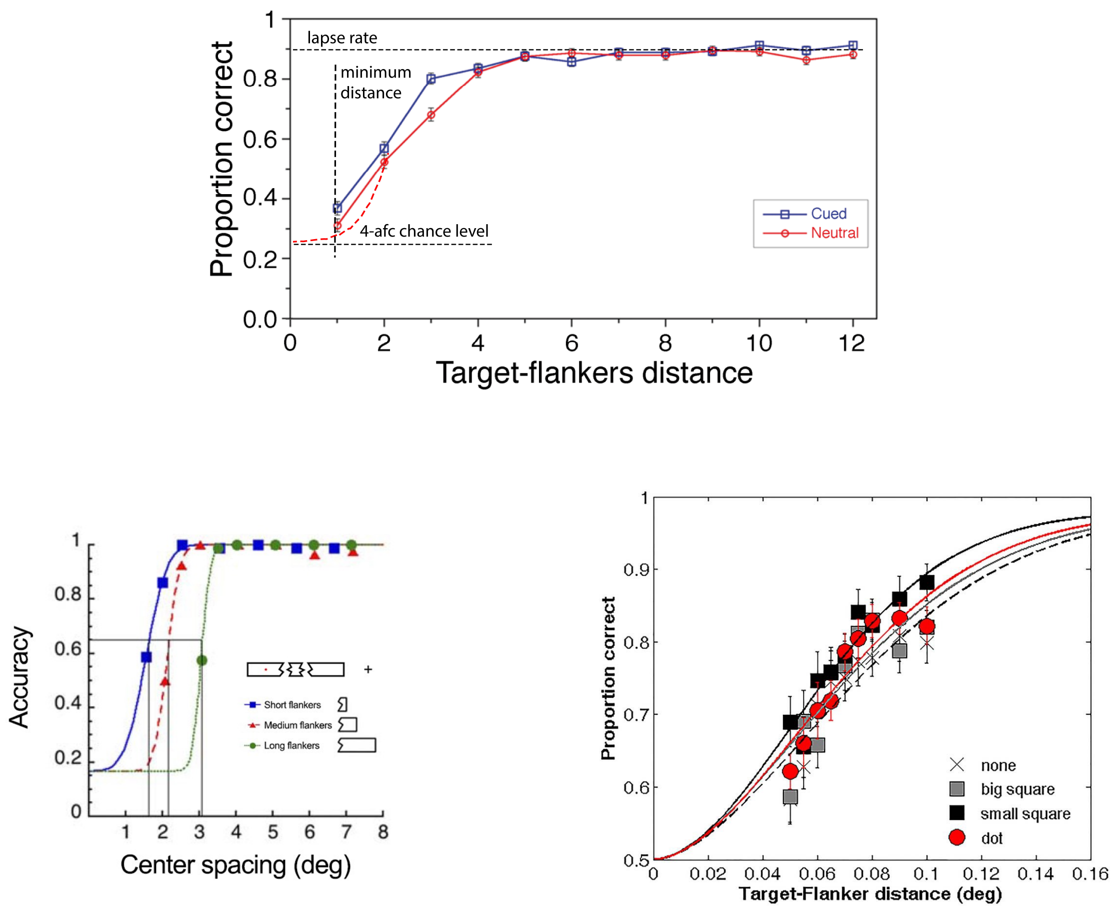

Figure 11. Psychometric functions vs. flanker distance. (a) For letter-T recognition (red line; disregard the blue line). Modified from Yeshurun & Rashal (2010, Fig. 5); (b) Example from Rosen, Chakravarthi, & Pelli, (2014, Fig. 9a) with novel patterns that allow widening the flankers; the inset shows the stimulus and the legend. (c) Another recent example, used for quantifying spatial attention (Albonico et al., 2018, Fig. 4).

From that psychometric function (p_c vs. flanker distance), together with Bouma's law (which describes critical distance vs. eccentricity), we can then 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. Examples where that is approximately the case would be letters on a printed page, or people in a crowd. Assume further that in the viewing direction 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 11). Figure 12a 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 (in the upward direction) in Figure 12b. The figure is obtained from

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Figure 12a by re-scaling the y-axis and flipping the graph horizontally and vertically, so that crowding (the downward arrow in Fig. 12a) goes upwards, and flanker distance *d* goes backwards. The y-axis now shows crowding, as standardly defined.

Finally, observe that Figure 12b 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 11 or Figure 12b shows proportion-correct vs. $(d-d_c)$, i.e. vs. flanker distance minus critical distance:

$$p_c = \Phi(d-d_c) \tag{3}$$

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

$$c = 1 - \lambda - p_c = 1 - \lambda - \Phi(d-d_c). \tag{4}$$

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., of d_c going backwards), centred at the mean object distance *d* (as in Figure 12b). Critical distance, expressed as empty space, is proportional to eccentricity φ by Bouma's law (eq. 1),

$$d_c = \beta\varphi \tag{5}$$

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

$$c = 1 - \lambda - \Phi(d - \beta\varphi) \tag{6}$$

as shown in Figure 12b.

For an intuitive understanding inspect Figure 12b again, starting from the left. In the centre of the visual field there is no crowding ($c = 0$) for the average task (like reading this paper). When eccentricity is increased, critical distance (understood as empty space) increases proportionally whereas recognition performance stays unaffected because critical distance is below the objects' distance. At some eccentricity (shown as a vertical dashed line), critical distance then 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 11 or 12a. A little further out in the visual field, behaviour is limited by chance performance and does not change further.

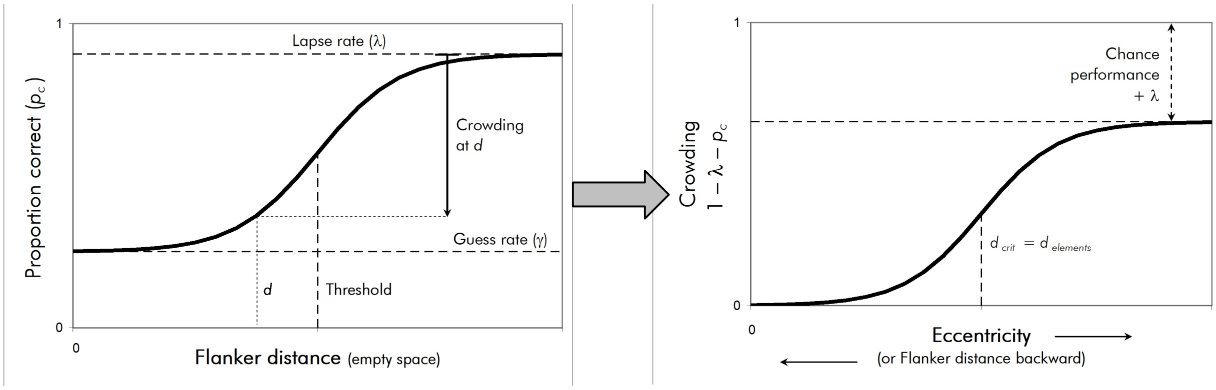

Figure 12. Schematic depiction of crowding, as defined standardly, i.e. as the impairment of recognition performance by the presence of flankers. (a) Psychometric function for proportion-correct performance in a crowding task, as in Figure 11. The effect of crowding, at some flanker distance *d*, is seen as the

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downward arrow on the right, starting from best performance (1–λ). (b) Crowding as in figure part a, but now as a function of eccentricity.

In summary, crowding's *spatial* extent increases linearly with eccentricity. Yet crowding's extent (or magnitude) understood in the standard way varies by a sigmoid function: Up to some small eccentricity, there is no crowding at all in most scenes. A little further out, there is suddenly full crowding (Figure 12b). Furthermore, when understood in the standard way, crowding cannot be compared to the MAR because they are measured on different dimensions (proportion correct vs. stimulus size). Yet if we compare the *effect* of crowding to the *effect of* the MAR (e.g. on visibility), crowding overrides the latter by far.

Crowding asymmetries

The influence of flankers in crowding depends on where in the visual field the flankers are relative to the target, and where the target is. The effects of that are known as *crowding asymmetries*. The one best known is the radial-tangential anisotropy described by Toet & Levi (1992), where flankers on the radius connecting the target to the visual-field centre exert more influence than those arranged tangentially, leading to the well-known, radially-elongated interaction fields (one of Toet & Levi's figures is reproduced online in Strasburger et al., 2011, Fig. 20, for illustration). This asymmetry is highly reliable and has been replicated many times (Petrov & Meleshkevich, 2011a; Kwon et al., 2014; Greenwood, Szinte, Sayim, & Cavanagh, 2017), including its counterpart in the cortical map obtained with fMRI measures (Kwon et al., 2014). Another robust asymmetry in crowding refers to the location of the target, for which it has been shown that crowding is stronger in the upper than in the lower visual field (He, Cavanagh, & Intriligator, 1996; Petrov & Meleshkevich, 2011a; Fortenbaugh, Silver, & Robertson, 2015; Greenwood et al., 2017).

In the present context, however, I wish to draw attention to an asymmetry where it turns out that it is much less clear-cut than the ones mentioned above: The inner-outer asymmetry, which compares the influence of a flanker closer to the visual-field centre to one more peripheral.[18]

Misconception 5a). The inner-outer asymmetry was found by Bouma (1970).

Again, the problem here is incautious phrasing. Crowding is indeed asymmetric in that flankers outward *in the visual field* play a different role than those more inward. However, authors like to cite Bouma's famous paper from 1970 for the original report of that asymmetry, which is incorrect. Indeed, Herman Bouma does mention the asymmetry in that short *Nature* letter – but he also warns that those were only pilot data on the asymmetry and he notes it only as an aside at the end of the letter. The credit must go to Norman Mackworth (1965) instead: Mackworth reported the asymmetry several years earlier and it is he to whom Bouma refers (both in his 1970 and his 1973 paper) (Figure 13).

Mackworth (1965): Bouma (1970):

[18] Note that it would not be correct to say 'temporal-nasal asymmetry', because it refers to the visual field, not the retina.

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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 …

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 13. Quotes on the central-peripheral (inward-outward) asymmetry of crowding, by Mackworth (1965) and Bouma (1970). Emphasis added.

To put Mackworth's quotation into context, an example for the end-of-the-line effect that he refers to in it – and which is separate from the asymmetry that we are concerned with here – is shown in Figure 14 (Haslerud & Clark, 1957, Fig. 1). 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 (i. e. those located most peripherally) 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 was at about ±3.5° eccentricity. Thus, already in these early experiments, the influence of eccentricity (i.e. reduced acuity) was clearly outweighed by less crowding for the first and last letter due to the adjacent empty space. Bouma (1973) reported a similar result, which is discussed by Levi (2008). Precursors of Haslerud & Clark (1957) for such experiments were by Benno Erdmann and Raymond Dodge (Erdmann & Dodge, 1898), and Julius Wagner (Wagner, 1918; e.g. on p. 53 he describes the better visibility of the first and last letter) (see Haslerud & Clark, 1957; Korte, 1923).

Bouma has also not really followed up much on the inward-outward asymmetry in the visual field; it is the left-right asymmetry and the recognition of inward versus outward letters *in a word* that he writes about later (Bouma, 1973) (see Figure 13 for the difference). The inward-outward asymmetry has instead been thoroughly investigated by Estes & Wolford (1971), Estes et al. (1976), Krumhansl (1977), Chastain & Lawson (1979), and Chastain (1982, 1983) (and more recently by Bex, Dakin & Simmers (2003), Petrov & Popple, 2007, Dayan & Solomon, 2010, Petrov & Meleshkevich, 2011b, and others). Unfairly, the older papers often get no credit in the vast current crowding literature (for reviews of the asymmetries see Strasburger & Malania, 2013, and Strasburger, 2014, Levi, 2008, and Dayan & Solomon, 2010).

So, in summary for that point, crowding is asymmetric with respect to the influence of the more peripheral vs. the more central flanker. That has been shown first by Mackworth (1965) in the context of the end-of-the-line effect and has been followed up by authors from experimental

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psychology like Estes, Krumhansl, and Chastain in the 70s and 80s, and later in vision research.

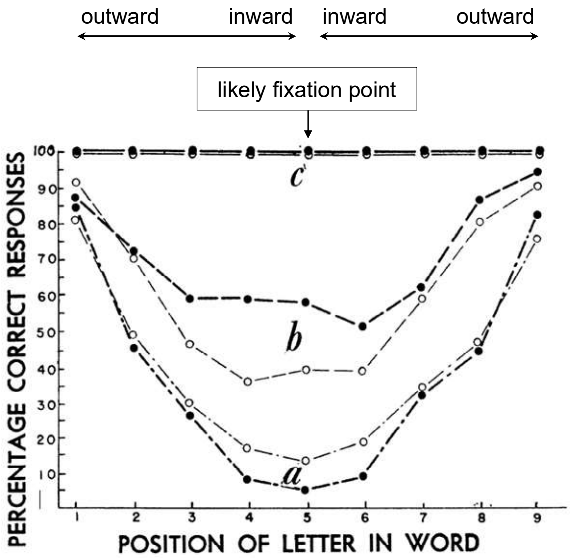

Figure 14. The end-of-the-line effect to which Mackworth (1965) refers (Haslerud & Clark, 1957). Letter recognition in 7.6°-wide nine-letter words. Open symbols: women; filled: men. *a:* fragmentary responses; *b:* incorrect; *c:* correct. Note that both the last and the first letter are *outside* in the visual field.

Misconception 5b). For the inner-outer asymmetry, the peripheral flanker has more effect.

There appears to be wide agreement that in the central-peripheral asymmetry (inward/outward in the visual field) the more peripheral flanker exerts more "adverse interaction" than the more central one (as Bouma, 1970, has put it)[19]. Bouma thus suggests that "the area of interaction is […] egg-shaped towards the retinal periphery", and this fits together well with the radially elongated interaction zones drawn by Toet & Levi (1992)[20].

But that unanimity is deceiving – the conclusion that the more peripheral flanker is always the more effective one is not that clear-cut as sometimes suggested. Even though the superior recognizability of the peripheral flanker is probably uncontroversial, the consequences of that for crowding are unclear. The opposite asymmetry was reported by Chastain (1982), who found that with increasing similarity of target and flankers, the *inward* flanker leads to more impairment of accuracy, i.e. plays the more important role. He further pointed out that the confusability increases with eccentricity. Furthermore, when Chastain (1982, p. 576) re-analysed Krumhansl's (1977) data it also supported the reverse asymmetry, counter to what was stated in her publication.

An opposite asymmetry was further reported more recently by Strasburger & Malania (2013), with an informal model for explanation in Strasburger (2014). The data there (shown here in Figure 15a) are from a reanalysis of results for the character-crowding task in Strasburger (2005). Part of the crowding effect (up to 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,

[19] If that sounds like a specialised question, note that it clashes with our understanding of the organisation of the visual field.
[20] Note that Toet & Levi (1992) used flankers on either side of the target whereas Bouma's (1970) pilot data was based on using only one flanker.

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that difference depended on eccentricity; it increased with eccentricity 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 formal and informal theories have been put forward to explain the central-peripheral asymmetry in crowding. Estes et al. (1976), e.g., distinguish item errors and “errors reflecting loss of positional information”, and with respect to the latter conclude that “transposition errors exhibit a pronounced peripheral-to-central drift”. Chastain (1983) suggests, “features from the peripheral nontarget could be mislocalized in a foveal direction to the target position”. Motter & Simoni, 2007 and Nandy & Tjan, 2012) invoke the laterally smaller representation of critical distance on the cortical map, though that account was shown to be insufficient as an explanation by Petrov and coworkers (Petrov, Popple, & McKee, 2007; Petrov & Meleshkevich, 2011b). Petrov & Meleshkevich (2011b) present evidence that the inner-outer asymmetry might be due to an inherent inner-outer asymmetry of (sustained) spatial attention: (1) The outward asymmetry mostly disappeared in diffused relative to focused attention, and (2) manipulation of the spatial-attentional conditions showed that the attentional field itself (the “spotlight”) was shifted outward in the visual field. Note that, by its implementation, spatial attention in Petrov & Meleshkevich’s study refers to *sustained* spatial attention, as in Strasburger & Rentschler, 1995, He et al., 1996, Strasburger, 2005, not to *transient* spatial attention as in Strasburger, 2005, Strasburger & Malania, 2013 (for the distinction see Nakayama & MacKeben, 1989).

However, none of these models attempts to explain the conflicting evidence with respect to the inward-outward asymmetry. The additional suggestion in Strasburger (2014) is to account for those conflicting asymmetry results by adding the influence of a mechanism not yet much considered in the crowding literature: feature binding as a part of the neural network dynamics in pattern processing (von der Malsburg, 1995). This computational concept is not necessarily linked to attention (i.e. is not to be understood in the sense of Treisman & Gelade, 1980), and is not quite captured by Treisman’s (1996) ‘Part binding’ category. Features in that framework could be as in Wolford’s (1975) Feature Perturbation Model, which in turn were taken from Lindsay & Norman (1972) (there were seven types of features there including vertical lines, acute angles, and continuous curves). Features to be considered should be of the same colour since crowding characteristics change when flankers have different colour or contrast polarity (Pelli et al., 2004). Greenwood, Bex & Dakin (2012) discuss models of how binding could be related to crowding, and Yu, Akau & Chung (2012) present a more recent discussion what the suitable candidates for features in word recognition could be.

Now, 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. Such models do not 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, and further suggest that it is

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location-dependent. Binding, whichever way implemented, 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 would thereby be more "stable" and tend to interfere as a whole. Peripheral flankers, in contrast, would tend to mix-in features with the target (Figure 15b).

This is not to say that confusions, in whole or in part, are the whole story. Crowding mechanisms other than confusions play a part and might further be stronger more peripherally (compared to more centrally). They could lead to a stronger overall interference of the peripheral flanker, consistent with the majority of findings on the asymmetry.[21]

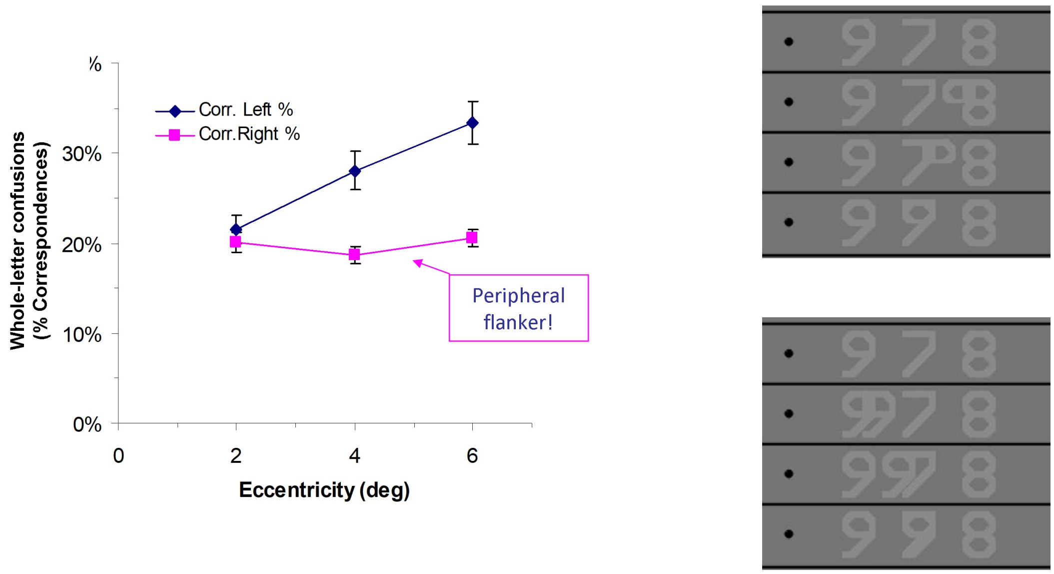

Figure15. (a) Reverse asymmetry in a crowding task reported in Strasburger & Malania, (2013, Fig. 8a) (modified). Confusions with the more central, but not the more peripheral, flanker depend on eccentricity. (b) Cartoon, as a memory aid for the mechanisms: (top) A peripheral letter part moving inward; (bottom) The more central flanker moving outward. Note that the cartoon does not quite capture the effect of features since these are a far more general concept than parts.

So in sum, neither of the flanking letters has just more effect in crowding; the suggestion here is that peripherally and centrally located flankers play different roles, and that the extent of that specific interference depends on eccentricity. How, exactly, will need more research.

Crowding in the cortical map

Misconception 6). Critical crowding distance corresponds to a constant cortical distance in V1 and other primary visual cortical areas.

We now go from visual psychophysics to cortical neurophysiology. Crowding is a cortical

[21] A (symmetric) model of word recognition that very successfully treats location errors and identification errors separately was recently presented by Bernard & Castet (2019). To quote from the paper, "This result suggests that letter position uncertainty is an important and overlooked factor limiting peripheral word recognition (and reading without central vision in general)." (p. 57)

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phenomenon; this is known since Flom, Weymouth & Kahneman's (1963) dichoptic experiments. We further know (since Inouye, 1909) that the primary visual cortex is retinotopically organized, i.e. that neighbouring points in the visual field project to neighbouring points in the primary visual cortex (and in later areas up to V4). We thus speak of the *cortical map* (see Schira, Tyler, Spehar, & Breakspear, 2010 or Schira, Tyler, & Rosa, 2012 for intuitive graphics). Now, crowding is about neighbourhood in the visual field and how close visual objects are. The question that then naturally arises is how close are these objects' representations in the cortical map? In particular, what are the critical distances for crowding in the cortical map(s)? Or, what is the equivalent of Bouma's law in the primary visual cortex?

Levi, Klein & Aitsebaomo (1985a, Fig. 15) found critical distance for a vernier target to be largely a constant in the cortex (~1 mm) by applying *M* scaling with the E_2 concept (they use a transformed eccentricity, $E^* = E + E_2$, with $E_2 = 0.8°$ for cortical processing and $E_2 = 2.5°$ for retinal processing). Motter & Simoni (2007) more generally proposed that Bouma's law translates to a *constant* critical distance on the cortical map above 10° eccentricity, i.e., that the linear increase in the visual field translates to a constant in the cortex (see the dashed line in Figure 16b below). Interestingly, however, their Fig. 7 shows a non-constant curve, similar to the one derived in Strasburger (2019), shown below (Figure 16b, continuous line). Pelli (2008) presented a mathematical derivation of that constancy, based on Schwartz's (1980) logarithmic cortical mapping rule. Nandy & Tjan (2012, p. 465) then took it one step further and derived that the cortical equivalent (the footprint) of critical distance amounts to about six hypercolumns. The answer to the question what Bouma's law looks like in the cortical map is of interest for our understanding of cortical architecture but is also of practical use for research; Mareschal, Morgan, & Solomon (2010), e.g., applied the constancy assumption to their question and analysis of contextual influences on perceived orientation. Beware that a different, but slightly erroneous, non-constant cortical critical distance rule was derived in (Strasburger et al., 2011, eq. 28, and Strasburger & Malania, 2013, eq. 13).

The constant-cortical-distance rule is appealing for its elegance and simplicity, and its derivation in Pelli (2008) is mathematically sound. It needs to be qualified, however: The constancy does likely not hold for the fovea. Looking closer, Schwartz (1980) has proposed two logarithmic mapping functions, a general and 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 4a), that Pelli (2008) used in his derivations (and Pelli warns against this limitation).

A corrected rule that includes the fovea is presented in Strasburger (2017d, 2019), shown in Figure 16 below. It was derived from the *cortical location function* which maps retinal location to cortical location and, as shown in that paper, can be stated as

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

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. The first, E_2, is Levi's value specifying at which eccentricity in the visual field the foveal value (of,

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for example, MAR) is doubled (Levi, Klein, & Aitsebaomo, 1984, Strasburger et al., 2011; see Footnote 5 and 13 above). The newly proposed parameter d_2 is E_2's counterpart in the cortical map: the distance of E_2's *representation* in the map from the retinotopic centre (that centre is roughly located 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

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

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 (in the text 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

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

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, is the eccentricity increment at which critical distance increases by the foveal value, δ_0).

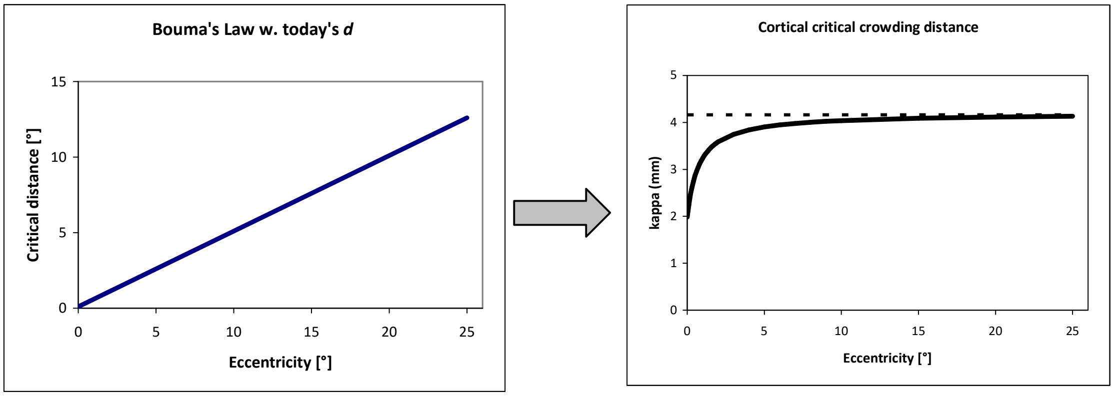

Figure 16. (a) Bouma's law in the visual field and (b) its cortical equivalent, i.e. how it translates to the cortical map in a primary visual area (Strasburger, 2019, Fig. 8; see there for the specific parameters chosen for the estimation and note that kappa depends upon these).

The graph of eq. (8) is shown in Figure 16b. Critical distance for crowding on the cortical map starts at some value in the retinotopic 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.

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Crowding research

Misconception 7). Except for Bouma's (1970) paper, crowding research mostly started in the 2000s.

Crowding is 'quite the rage' in vision research these days; a very modern enterprise it is. The above statement is of course a caricature but I do feel that the strong pertinent research tradition from the sixties, seventies, and eighties, as well as the initial paper by Korte (1923), do not get the credit they deserve. Not only are papers from that time rarely cited, many scholars also do not know what is said there (and are blissfully unaware that what is reported in them might precede one's own ideas – after all, it is good scientific practice 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, and consequently do not show up in a search for *crowding*:

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

One might argue 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 yet led to reliable distinctions. That is not to say such attempts were fruitless or 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 keywords in standard search machines.

Another, somewhat trivial reason for the neglect, at least for a while, might have been that full-text versions of older papers were not available online. I still have my collection of reprints from the 1980s and 90s. In the comparably young history of crowding research, that change of reading and writing habits away from printed material must have had an influence. Digitization of the older literature is not complete (e.g. *Clinical Vision Sciences* is missing); that of the 19th-century and before is still an ongoing process (a good source for the latter is the *Internet Archive,* https://archive.org/, from where we retrieved historic papers by Helmholtz, Volkmann, and Wülfing for Strasburger, Huber, & Rose, 2018).

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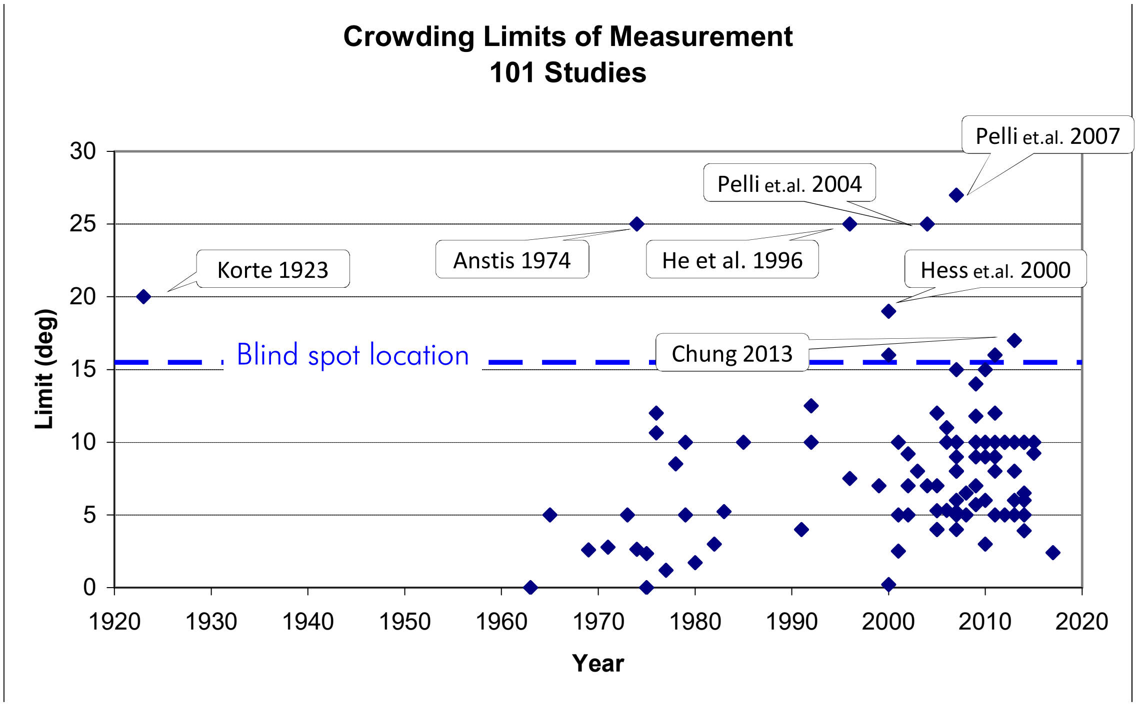

Figure 17. Essential crowding literature from 1923 to 2004. Abscissa: year of publication; ordinate: eccentricity in the visual field up to which crowding was studied in the paper. (References given in Figure 18.)

Figure 17 shows a chart of crowding literature up to the present. Note 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 15.5° marks the blind spot (on the horizontal meridian) as a reference (Rohrschneider, 2004).

There are four points I wish to make: (1) The vast majority of studies are concerned with quite small eccentricities (cf. Misconception #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 has been 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) With respect to the year 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 in the graph (Ehlers 1936, 1953, are not listed since they present no data). Filling the gap might need more digging in the older literature. Another reason from that break, however, could be the expulsion of Gestalt psychologists from Germany, who were those interested in visual phenomena at that time.

Figure 18 gives the references for the papers in that graph. Those in bold print might be seen as landmark papers, but this is of course a subjective view.

Crowding research, 1923 – 2004

Autors	Year	Limit °
Korte	1923	**20**
Ehlers	1936/'53	--
Stuart & Burian	1962	0
Flom, Weymouth & Kahneman	1963	0
Mackworth	1965	5
Shaw	1969	2.6
Townend, Taylor & Brown	1971	2.8
Bouma	1973	5
Anstis	1974	**25**
Wolford & Hollingsworth	1974	2.6
Wolford	1975	2.3
Westheimer & Hauske	1975	0
Andriessen & Bouma	1976	12
Estes, Allmeyer & Reder	1976	10.6
Krumhansl & Thomas	1977	1.2
Loomis	1978	8.5
Banks et al.	1979	5
Jacobs	1979	10
Wolford & Shum	1980	1.7
Chastain	1982	3

Autors	Year	Limit °
Wolford & Chambers	1983	5.2
Levi, Klein & Aitsebaomo	1985	10
Strasburger, Harvey & Rentschler	1991	4
Geiger, Lettvin & Zegarra-Moran	1992	12.5
Toet & Levi	1992	10
He, Cavanagh & Intriligator	1996	**25**
Higgins, Arditi & Knoblauch	1996	7.5
Huckauf, Heller & Nazir	1999	7
Hess, Dakin, Kapoor & Tewfik	2000	19
Liu & Arditi	2000	0.2
Xing & Heeger	2000	16
Chung, Levi & Legge	2001	5
Fine	2001	10
Parkes, Lund, Agelucci, Solomon, Morgan	2001	2.5
Huckauf & Heller	2002	7
Levi, Hariharan & Klein	2002	5
Tripathy & Cavanagh	2002	9.2
Bex et al.	2003	8
Huckauf & Heller	2004	7
Pelli, Palomares & Majaj	2004	**25**

Figure 18. Crowding literature from 1923 to 2004 shown in Figure 17. Bold print: Particularly important papers. The last column shows (as before) the eccentricity in the visual field up to which crowding was studied.

Crowding research before 1923

Ehlers (1936) in the above list is 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 on crowding before that?

Surprisingly, phenomena that today we would interpret as *crowding* were already described in writing a thousand years ago, by Ibn Al-Haytham (latinised *Alhazen*; 965–1039, Figure 19a, Strasburger & Wade, 2015a). This is as early as vision was explained – like today – "as the outcome of the formation of an image in the eye due to light" (Russell, 1996) (before that, vision was explained by rays emanating *from* the eye).

Here is a description from al-Haytham's "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

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> 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 that experiment. So the "confused and obscure" percept that he describes arises from crowding. The only ingredient missing for an experimental unveiling of crowding was a direct comparison with single letters at the respective eccentric location, which he could have easily done with his apparatus.

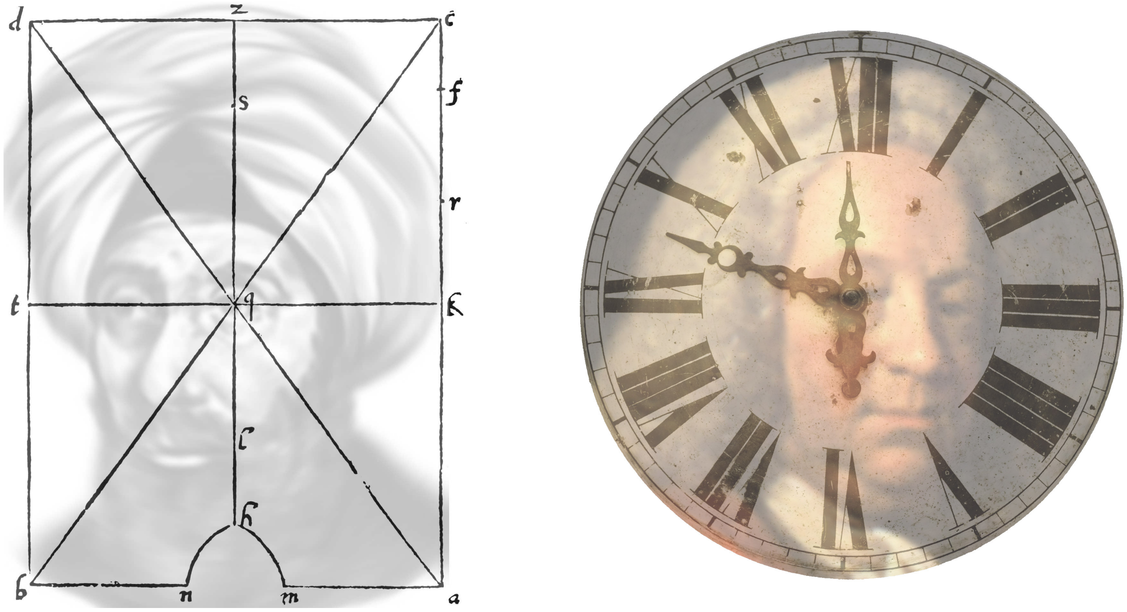

Figure 19. (a) Portrait of Ibn al-Haytham (c. 965 – c. 1040), with his perimeter superimposed (from Strasburger & Wade, 2015b). (b) Portrait of James Jurin (1684 – 1750) with a clock face superimposed, as the one described in his text and common at the time. Note that the number *Four* is not in correct 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, Figure 19b):

> "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 Jurin's essay where the stimuli are likely to have elicited crowding in the percept:

> ''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:

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> ‘’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 – by virtue of 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 was said above might be obvious. Or, on the other end of the spectrum, one might disagree with some points. The points made above are also not all equally important and are not all of general interest. However, 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[22]. 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.

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References

Adler, F. H. (1959). *Physiology of the eye: Clinical application* (3 ed.). St. Louis: Mosby.

Albonico, A., Martelli, M., Bricolo, E., Frasson, E., & Daini, R. (2018). Focusing and orienting spatial attention differently modulate crowding in central and peripheral vision. *Journal of Vision, 18(3):4*, 1–17.

Anderson, D. R. (1987). *Perimetry with and without automation* (2 ed.). St Louis: C. V. Mosby.

[22] Is there a Weber-Fechner law? Or is that a *textbook hoax*? (in German a “*textbook duck*”). Or, which term is correct: “chi-squared” or “chi-square”?

Andriessen, J. J., & Bouma, H. (1976). Eccentric vision: Adverse interactions between line segments. *Vision Research, 16*(1), 71-78.

Anstis, S. M. (1974). A chart demonstrating variations in acuity with retinal position. *Vision Res, 14*, 589-592.

Aulhorn, E. (1964). Über die Beziehung zwischen Lichtsinn und Sehschärfe. *Albrecht von Graefes Archiv für klinische und experimentelle Ophthalmologie, 167*, 4-74.

Axenfeld, T., & Pau, H. (1992). *Lehrbuch der Augenheilkunde* (13 ed.). Stuttgart, Jena, New York: Gustav Fischer.

Bach, M. (2017). Mythen der Sinnesphysiologie [Myths of sensory physiology]. *Zeitschrift für praktische Augenheilkunde, 38*, 435–437.

Balas, B., Nakano, L., & Rosenholtz, R. (2009). A summary-statistic representation in peripheral vision explains visual crowding. *Journal of Vision, 9*(12), 1–18.

Banks, W. P., Larson, D. W., & Prinzmetal, W. (1979). Asymmetry of visual interference. *Perception & Psychophysics, 25*(6), 447-456.

Barlow, H. B. (1957). Increment thresholds at low intensities considered as signal/noise discriminations. *The Journal of Physiology, 136*(3), 469-488.

Bernard, J.-B., & Castet, E. (2019). The optimal use of non-optimal letter information in foveal and parafoveal word recognition. *Vision Research, 155*, 44-61.

Bex, P. J., Dakin, S. C., & Simmers, A. J. (2003). The shape and size of crowding for moving targets. *Vision Research, 43*, 2895-2904.

Bonneh, Y., & Sagi, D. (1999). Configuration saliency revealed in short duration binocular rivalry. *Vision Research, 39*, 271–281.

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research, 13*, 767-782.

Bouma, M. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*, 177-178.

Chakravarthi, R., & Pelli, D. G. (2011). The same binding in contour integration and crowding. *Journal of Vision, 11(8):10*, 1–12.

Chastain, G. (1982). Confusability and interference between members of parafoveal letter pairs. *Perception & Psychophysics, 32*(6), 576·580.

Chastain, G. (1983). Task and contrast effects on performance with parafoveal stimulus pairs. *Psychological Research, 45*, 147–156.

Chastain, G., & Lawson, L. (1979). identification asymmetry of parafoveal stimulus pairs. *Perception & Psychophysics, 26*, 363-368.

Chung, S. T. L., Legge, G. E., & Ortiz, A. (2003). Precision of local signs for letters in central and peripheral vision [Abstract]. *Journal of Vision, 3*(9), 815, 815a.

Chung, S. T. L., Levi, D. M., & Legge, G. E. (2001). Spatial-frequency and contrast properties of crowding. *Vision Research, 41*(14), 1833-1850.

Coates, D. R., & Levi, D. M. (2014). Contour interaction in foveal vision: A response to Siderov, Waugh, and Bedell (2013). *Vision Research, 96*, 140–144.

Coates, D. R., Levi, D. M., Touch, P., & Sabesan, R. (2018). Foveal Crowding Resolved. *Scientific Reports, 8*(1), 9177.

Collier, R. M. (1931). An experimental study of form perception in indirect vision. *Journal of Comparative Psychology, 11*(3), 281-290.

Dayan, P., & Solomon, J. A. (2010). Selective Bayes: Attentional load and crowding. *Vision Research, 50*, 2248–2260.

Diepes, H., Krause, K., & Rohrschneider, K. (2007). *Sehbehinderung; Ursachen – Auswirkungen – Versorgung [Visual Impairment: Causes – Effects – Care]*. Heidelberg: DOZ-Verlag Optische Fachveröffentlichung.

Duke-Elder, S. (1962). *System of ophthalmology (Vol. 6)*. London: Henry Kimpton.

Ehlers, H. (1936). The movements of the eyes during reading. *Acta Ophthalmologica, 14*, 56-63.

Ehlers, H. E. (1953). Clinical testing of visual acuity. *AMA Archiches of Ophthalmology, 49*, 431-434.

Erdmann, & Dodge. (1898). *Psychologische Untersuchungen über das Lesen*. Halle.

Estes, W. K., Allmeyer, D. H., & Reder, S. M. (1976). Serial position functions for letter identification at brief and extended exposure durations. *Perception & Psychophysics, 19*, 1–15.

Estes, W. K., & Wolford, G. L. (1971). Effects of spaces on report from tachistoscopically presented letter strings. *Psychonomic Science, 25*, 77-80.

Fechner, G. T. (1860). *Elemente der Psychophysik*. Leipzig: Breitkopf und Härtel.

Fine, E. M. (2001). Does meaning matter? The impact of word knowledge on lateral masking. *Optometry and Vision Science, 78*(11), 831-838.

Fischer, F. P. (1924). Über Asymmetrien des Gesichtssinnes, speziell des Raumsinnes beider Augen. *Pflügers Archiv der gesamten Physiologie, 204*, 203-233.

Fischer, F. P., & Wagenaar, J. W. (1954). Binocular vision and fusion movements. *Documenta Ophthalmologica, 7*(1), 359-391.

Flom, M. C., Weymouth, F. W., & Kahneman, D. (1963). Visual resolution and contour interaction. J. Opt. Soc. Am. 53, 1026-1032.

Fortenbaugh, F. C., Silver, M. A., & Robertson, L. C. (2015). Individual differences in visual field shape modulate the effects of attention on the lower visual field advantage in crowding. *Journal of Vision, 15(2):19*, 1-15.

Freeman, J., Chakravarthi, R., & Pelli, D. G. (2012). Substitution and pooling in crowding. *Attention, Perception, & Psychophysics, 74*, 379-396.

Geiger, G., Lettvin, J. Y., & Zegarra-Moran, O. (1992). Task-determined strategies of visual process. *Cognitive Brain Research, 1*(1), 39-52.

Goldstein, E. B. (2002). *Sensation and Perception* (6th ed.). Pacific Grove, CA, USA: Wadsworth.

Greenwood, J. A., Bex, P. J., & Dakin, S. C. (2012). Crowding follows the binding of relative position and orientation. *Journal of Vision, 12(3):18*, 1–20.

Greenwood, J. A., Szinte, M., Sayim, B., & Cavanagh, P. (2017). Variations in crowding, saccadic precision, and spatial localization reveal the shared topology of spatial vision. *Proceedings of the National Academy of Sciences, 114*(17), E3573-E3582.

Gurnsey, R., Roddy, G., & Chanab, W. l. (2011). Crowding is size and eccentricity dependent. *Journal of Vision, 11*(7, 15), 1-17.

Haslerud, G. M., & Clark, R. E. (1957). On the redintegrative perception of words. *American Journal of Psychology, 70*, 97-101.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature, 383*, 334-337.

Herzog, M. H., & Manassi, M. (2015). Uncorking the bottleneck of crowding: a fresh look at object recognition. *Current Opinion in Behavioral Sciences*(1), 86–93.

Herzog, M. H., Sayim, B., Chicherov, V., & Manassi, M. (2015). Crowding, grouping, and object recognition: A matter of appearance. *Journal of Vision, 15(6):5*, 1-18.

Hess, R. F., Dakin, S. C., Kapoor, N., & Tewfik, M. (2000). Contour interaction in fovea and periphery. *Journal of the Optical Society of America A, 17*(9), 1516-1524.

Higgins, K. E., Arditi, A., & Knoblauch, K. (1996). Detection and identification of mirror-image letter pairs in central and peripheral vision. *Vision Research, 36*(2), 331-337. Further in: Tyler, Christopher W. (Ed): *Human symmetry perception.*AH Zeist, VSP, 371-383.

Holladay, J. T., & Simpson, M. J. (2017). Negative dysphotopsia: Causes and rationale for prevention and treatment. *Journal of Cataract and Refractive Surgery, 43*, 263–275.

Howard, I. P., & Rogers, B. J. (2012). *Perceiving in Depth* (Vol. 2). Oxford: Oxford University Press.

Huckauf, A., & Heller, D. (2002). What various kinds of errors tell us about lateral masking effects. *Visual Cognition, 9*(7), 889-910.

Huckauf, A., & Heller, D. (2004). On the relations between crowding and visual masking. *Percept Psychophys, 66*(4), 584-595.

Huckauf, A., Heller, D., & Nazir, T. A. (1999). Lateral masking: limitations of the feature interaction account. *Perception & Psychophysics, 61*(1), 177-189.

Hueck, A. (1840). Von den Gränzen des Sehvermögens [On the limits of sight]. *Archiv für Anatomie, Physiologie und wissenschaftliche Medicin*, 82-97.

Inouye, T. (1909). *Die Sehstörungen bei Schussverletzungen der kortikalen Sehsphäre*. Leipzig: W. Engelmann.

Jacobs, R. J. (1979). Visual resolution and contour interaction in the fovea and periphery. *Vision Research, 19*(11), 1187-1195.

Jurin, J. (1738). An essay on distinct and indistinct vision. In *A compleat system of opticks in four books, viz. a popular, a mathematical a mechanical, and a philosophical treatise* (pp. 115-171). Cambridge: Published by the author.

Karnath, H.-O., & Thier, P. E. (2006). *Neuropsychologie [Neuropsychology]* (2 ed.). Berlin u.a.: Springer.

Keshvari, S., & Rosenholtz, R. (2013). A high-dimensional pooling model accounts for seemingly conflicting substitution effects in crowding. *Journal of Vision, 13*(9), 576.

Korte, W. (1923). Über die Gestaltauffassung im indirekten Sehen (On the apprehension of Gestalt in indirect vision). *Zeitschrift für Psychologie, 93*, 17-82.

Krumhansl, C. L. (1977). Naming and locating simultaneously and sequentially presented letters. *Perception & Psychophysics, 22*(3), 293-302.

Krumhansl, C. L., & Thomas, E. A. C. (1977). Effect of level of confusability on reporting letters from briefly presented visual displays. *Perception and Psychophysics, 21*(3), 269–279.

Kuhn, T. S. (1962). *The Structure of Scientific Revolutions*: University of Chicago Press.

Kwon, M., Bao, P., Millin, R., & Tjan, B. S. (2014). Radial-tangential anisotropy of crowding in the early visual areas. *Journal of Neurophysiology 112*, 2413–2422.

Lachenmayr, B. J., & Vivell, P. M. O. (1992). *Perimetrie*. Stuttgart: Georg Thieme Verlag.

Le Grand, Y. (1957). *Light, Colour and Vision* (J. W. T. W. R.W.G. Hunt, and F.R.W. Hunt, Trans.). London: Chapman and Hall.

Levi, D. M. (2008). Crowding – an essential bottleneck for object recognition: a minireview. *Vision Research, 48*(5), 635-654.

Levi, D. M., & Carney, T. (2009). Crowding in peripheral vision: Why bigger Is better. *Current Biology, 19*(December 15), 1988–1993.

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Levi, D. M., Hariharan, S., & Klein, S. A. (2002a). Suppressive and facilitatory spatial interactions in peripheral vision: Peripheral crowding is neither size invariant nor simple contrast masking. *Journal of Vision, 2*(2).

Levi, D. M., Klein, S. A., & Aitsebaomo, A., P. (1985a). Vernier acuity, crowding and cortical magnification. *Vision Research, 25*, 963-977.

Levi, D. M., Klein, S. A., & Aitsebaomo, A. P. (1984). Detection and discrimination of the direction of motion in central and peripheral vision of normal and amblyopic observers. *Vision Research, 24*, 789-800.

Levi, D. M., Klein, S. A., & Aitsebaomo, A. P. (1985b). Vernier acuity, crowding and cortical magnification. *Vision Research, 25*, 963-977.

Levi, D. M., Klein, S. A., & Hariharan, S. (2002b). Suppressive and facilitatory spatial interactions in foveal vision: Foveal crowding is simple contrast masking. *Journal of Vision, 2*(2).

Li, K. Y., Tiruveedhula, P., & Roorda, A. (2010). Intersubject Variability of Foveal Cone Photoreceptor Density in Relation to Eye Length. *Invest. Ophthalmol. Vis. Sci., 51*(12), 6858-6867.

Lindsay, P. H., & Norman, D. A. (1972). *Human information processing: An introduction to psychology*. New York and London: Academic Press.

Liu, L., & Arditi, A. (2000). Apparent string shortening concomitant with letter crowding. *Vision Research, 40*, 1059–1067.

Livne, T., & Sagi, D. (2007). Configuration influence on crowding. *Journal of Vision, 7*(2), 1-12.

Livne, T., & Sagi, D. (2010). How do flankers' relations affect crowding? *Jounal of Vision, 10*(3), 1-14.

Loomis, J. M. (1978). Lateral masking in foveal and eccentric vision. *Vision Research, 18*(3), 335-338.

Mackworth, N. H. (1965). Visual noise causes tunnel vision. *Psychonomic Science, 3*, 67-68.

Malania, M., Herzog, M. H., & Westheimer, G. (2007). Grouping of contextual elements that affect vernier thresholds. *Journal of Vision, 7*(2), 1-7.

Manassi, M., Sayim, B., & Herzog, M. H. (2012). Grouping, pooling, and when bigger is better in visual crowding. *Journal of Vision, 12(10):13*, 1–14.

Manassi, M., Sayim, B., & Herzog, M. H. (2013). When crowding of crowding leads to uncrowding. *Journal of Vision, 13(13):10*, 1–10.

Mareschal, I., Morgan, M. J., & Solomon, J. A. (2010). Cortical distance determines whether flankers cause crowding or the tilt illusion. *Journal of Vision, 10*(8), 13:11-14.

Mathur, A., Gehrmann, J., & Atchison, D. A. (2013). Pupil shape as viewed along the horizontal visual field. *Journal of Vision, 13*(3), 1–8.

Menzer, G. W., & Thurmond, J. B. (1970). Form identification in peripheral vision. *Perception & Psychophysics, 8*(4), 205-209.

Motter, B. C., & Simoni, D. A. (2007). The roles of cortical image separation and size in active visual search performance. *Journal of Vision, 7*(2:6), 1–15.

Mütze, K. (1961). *ABC der Optik [ABC of Optics]*. Hanau/Main: Dausien.

Nakayama, K., & MacKeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29*(11), 1631-1647.

Nandy, A. S., & Tjan, B. S. (2012). Saccade-confounded image statistics explain visual crowding. *Nature Neuroscience, 15*(3), 463-471.

Parkes, L., Lund, J., Angelucci, A., Solomon, J. A., & Morgan, M. (2001). Compulsory averaging of crowded orientation signals in human vision. *Nature Neuroscience, 4*(7), 739-744.

Pelli, D. G. (2008). Crowding: a cortical constraint on object recognition. *Current Opinion in Neurobiology, 18*, 445–451.

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision, 4*(12), 1136-1169.

Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature Neuroscience, 11*(10), 1129-1135 (plus online supplement).

Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D., & Majaj, N. J. (2007). Crowding and eccentricity determine reading rate. *Journal of Vision, 7*(2).

Petrov, Y., & Meleshkevich, O. (2011a). Asymmetries and idiosyncratic hot spots in crowding. *Vision Research, 51*(10), 1117-1123.

Petrov, Y., & Meleshkevich, O. (2011b). Locus of spatial attention determines inward-outward anisotropy in crowding. *Journal of Vision, 11*(4), 1-11.

Petrov, Y., & Popple, A. V. (2007). Crowding is directed to the fovea and preserves only feature contrast. *Journal of Vision, 7*(2), 1-9.

Petrov, Y., Popple, A. V., & McKee, S. P. (2007). Crowding and surround suppression: Not to be confused. *Journal of Vision, 7*(2), 1-9.

Piccolino, M., & Wade, N. J. (2013). The frog's dancing master: Science, séances, and the transmission of myths. *Journal of the History of the Neurosciences: Basic and Clinical Perspectives, 22*(1), 79-95.

Polyak, S. L. (1941). *The retina*. Oxford, England: Univ. Chicago Press.

Pöppel, E., & Harvey, L. O., Jr. (1973). Light-difference threshold and subjective brightness in the periphery of the visual field. *Psychologische Forschung, 36*, 145-161.

Purkinje, J. E. J. (1825). *Neue Beiträge zur Kenntniss des Sehens in subjectiver Hinsicht*. Berlin: G. Reimer.

Rayner, K. (1979). Eye Guidance in Reading: Fixation Locations within Words. *Perception, 8*(1), 21-30.

Rekdal, O. B. (2014). Academic urban legends. *Social Studies of Science, 44*(4), 638-654.

Rohrschneider, K. (2004). Determination of the location of the fovea on the fundus. *Investigative Ophthalmology & Visual Science, 45*(9), 3257-3258.

Rönne, H. (1915). Zur Theorie und Technik der Bjerrrumschen Gesichtsfelduntersuchung. *Archiv für Augenheilkunde, 78*(4), 284–301.

Rosen, S., Chakravarthi, R., & Pelli, D. G. (2014). The Bouma law of crowding, revised: Critical spacing is equal across parts, not objects. *Journal of Vision, 14(6):10*, 1-15.

Rosenholtz, R. (2015). Texture perception. In J. Wagemans (Ed.), *The Oxford Handbook of Perceptual Organization* (pp. 167-186). Oxford: Oxford University Press.

Rosenholtz, R. (2016). Capabilities and limitations of peripheral vision. *Annual Review of Vision Science, 2*, 437–457.

Russell, G. A. (1996). The emergence of physiological optics. In R. Rashed & R. Morelon (Eds.), *Encyclopedia of the History of Arabic Science* (Vol. 2, pp. 672-715). London, New York: Routledge.

Saarela, T. P., Sayim, B., Westheimer, G., & Herzog, M. H. (2009). Global stimulus configuration modulates crowding. *Journal of Vision, 9(2):5*, 1–11.

Schira, M. M., Tyler, C. W., & Rosa, M. G. P. (2012). Brain mapping: The (un)folding of striate cortex. *Current Biology, 22*(24), R1051-R1053.

Schira, M. M., Tyler, C. W., Spehar, B., & Breakspear, M. (2010). Modeling magnification and anisotropy in the primate foveal confluence. *PLoS Computational Biology, 6*(1), e1000651.

Schober, H. (1970). *Das Sehen [Vision]*. Leipzig: VEB Fachbuchverlag.

Schwartz, E. L. (1980). Computational anatomy and functional architecture of striate cortex: A spatial mapping approach to perceptual coding. *Vision Research, 20*, 645-669.

Sekuler, R., & Blake, R. (1994). *Perception* (3 ed.). New York: McGraw-Hill.

Shaw, P. (1969). Processing of tachistoscopic displays with controlled order of characters and spaces. *Perc. & Psychophys, 6*, 257-266.

Siderov, J., Waugh, S. J., & Bedell, H. E. (2013). Foveal contour interaction for low contrast acuity targets. *Vision Research, 77*, 10–13.

Siderov, J., Waugh, S. J., & Bedell, H. E. (2014). Foveal contour interaction on the edge: response to 'letter-to-the-editor' by Drs. Coates and Levi. *Vision Research, 96*, 145-148.

Simonsza, H. J., & Wade, N. J. (2018). Why did Donders, after describing pseudotorsion, deny the existence of ocular counterrolling together with Ruete, Volkmann, von Graefe and von Helmholtz, until Javal reconfirmed its existence? *Strabismus, 26*(4), 211-222.

Simpson, M. J. (2017). Mini-review: Far peripheral vision. *Vision Research, 140*, 96-105.

Snowden, R., Thompson, P., & Troscianko, T. (2006). *Basic Vision. An introduction to visual perception* (1st ed.). Oxford, New York: Oxford University Press.

Strasburger, H. (2001a). Converting between measures of slope of the psychometric function. *Perception & Psychophysics, 63*(8 (special issue *Psychometric Functions and Adaptive Methods*)), 1348-1355.

Strasburger, H. (2001b). Invariance of the psychometric function for letter recognition across the visual field. *Perception & Psychophysics, 63*(8 (special issue *Psychometric Functions and Adaptive Methods*)), 1356-1376.

Strasburger, H. (2005). Unfocussed spatial attention underlies the crowding effect in indirect form vision. *Journal of Vision, 5*(11), 1024-1037.

Strasburger, H. (2014). Dancing letters and ticks that buzz around aimlessly – on the origin of crowding. *Perception; Special Issue Illusions and Delusions, 43*(9), 963-976.

Strasburger, H. (2017a). *Far peripheral vision and pattern recognition. Symposium "Eye movements and the peripheral retina: Yarbus's ideas and current data".* Paper presented at the ECVP 2017, Berlin.

Strasburger, H. (2017b). *Geht das Gesichtsfeld locker über 100° schläfenwärts? Bericht aus der Sammlung der Lehrbuch-Enten (Does the visual field easily extend beyond 100°? A report from the collection of textbook ducks.) Poster*, Lingelbachs Scheune.

Strasburger, H. (2017c). Geht das Gesichtsfeld locker über 100° schläfenwärts? Bericht aus der Sammlung der Lehrbuch-Enten (Does the visual field easily extend beyond 100°? A report from the collection of textbook ducks.) Poster at Lingelbachs Scheune. *F1000Research, 6:1685*.

Strasburger, H. (2017d). On the cortical mapping function (ECVP 2017, Berlin). *F1000Research 2017, 6:1772*.

Strasburger, H. (2018). Seven myths on crowding [Electronic Version]. *PeerJ Preprints* from https://doi.org/10.7287/peerj.preprints.27250v1.

Strasburger, H. (2019). On the cortical mapping function (Preprint). *BioRXiv, 10.1101/621458*.

Strasburger, H., Bach, M., & Heinrich, S. P. (2018). Blur Unblurred – a Mini Tutorial. *i-Perception*, in print.

Strasburger, H., Harvey, L. O. J., & Rentschler, I. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception & Psychophysics, 49*, 495-508.

Strasburger, H., Huber, J., & Rose, D. (2018). Ewald Hering (1899) On the Limits of Visual Acuity: A Translation and Commentary. With a Supplement on Alfred Volkmann (1863) Physiological Investigations in the Field of Optics. *i-Perception*, in print.

Strasburger, H., & Malania, M. (2013). Source confusion is a major cause of crowding. *Journal of Vision, 13*(1), 1-20.

Strasburger, H., & Rentschler, I. (1995). Is the crowding effect of purely attentional origin? *Perception, 24, Suppl.*, 77.

Strasburger, H., Rentschler, I., & Jüttner, M. (2011). Peripheral vision and pattern recognition: a review. *Journal of Vision, 11*(5), 1-82.

Strasburger, H., & Wade, N. J. (2015a). James Jurin (1684–1750): A pioneer of crowding research? *Journal of Vision, 15*(1:9), 1-7.

Strasburger, H., & Wade, N. J. (2015b). James Jurin (1684–1750): A pioneer of crowding research? Poster presented at the ECVP 2015, Liverpool. *F1000Research, 4:675*.

Stuart, J. A., & Burian, H. M. (1962). A study of separation difficulty: its relationship to visual acuity in normal and amblyopic eyes. *American Journal of Ophthalmology, 53*, 471-477.

Toet, A., & Levi, D. M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research, 32*(7), 1349-1357.

Townsend, J. T., Taylor, S. G., & Brown, D., R. (1971). Lateral masking for letters with unlimited viewing time. *Perception & Psychophysics, 10*, 375-378.

Traquair, H. M. (1938). *An Introduction to Clinical Perimetry, Chpt. 1*. London: Henry Kimpton.

Treisman, A. (1996). The binding problem. *Current Opinion in Neurobiology, 6*(2), 171-178.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12*, 97-136.

Trendelenburg, W. (1961). *Der Gesichtssinn: Grundzüge der physiologischen Optik. Lehrbuch der Physiologie [The Sense of Sight: Fundamentals of Physiological Optics. Textbook of Physiology]*. Berlin: Springer.

Tripathy, S. P., & Cavanagh, P. (2002). The extent of crowding in peripheral vision does not scale with target size. *Vision Research, 42*, 2357–2369.

Tyler, C. W., & Likova, L. T. (2007). Crowding: A neuroanalytic approach. *Journal of Vision, 7*(2), 1–9.

van den Berg, R., Roerdink, J. B. T. M., & Cornelissen, F. W. (2007). On the generality of crowding: Visual crowding in size, saturation, and hue compared to orientation. *Journal of Vision, 7*(2), 1-11.

Van der Burg, E., Olivers, C. N. L., & Cass, J. (2017). Evolving the Keys to Visual Crowding. *Journal of Experimental Psychology: Human Perception and Performance, 43*(4), 690–699.

von der Malsburg, C. (1995). Binding in models of perception and brain function. *Current Opinion in Neurobiology, 5*(4), 520-526.

Vonthein, R., Rauscher, S., Paetzold, J., Nowomiejska, K., Krapp, E., Hermann, A., et al. (2007). The normal age-corrected and reaction time–corrected isopter derived by semiautomated kinetic perimetry. *Ophthalmology, 114*, 1065-1072.

Vul, E., Hanus, D., & Kanwisher, N. (2009). Attention as Inference: Selection Is Probabilistic; Responses Are All-or-None Samples. *Journal of Experimental Psychology: General, 138*(4), 546-560.

Wade, N. J. (1998). *A Natural History of Vision (A Bradford Book)*. Cambridge: MIT Press.

Wade, N. J., & Swanston, M. T. (1991). *Visual Perception: An Introduction*. London: Routledge.

Wagner, J. (1918). Experimentelle Beitrage zur Psychologie des Lesens. *Zeitschrift f. Psychologie, 80*, 1-75.

Wandell, B. A. (1995). *Foundations of vision*. Sunderland, MA: Sinauer Ass.

Wedekind, C. (Artist). (2014). *Wimmelbild about the 31st Chaos Communication Congress (31C3) in Hamburg* [Wikimedia Commons].

Westheimer, G., & Hauske, G. (1975). Temporal and spatial interference with vernier acuity. *Vision Research, 15*, 1137-1141.

Weymouth, F. W. (1958). Visual sensory units and the minimal angle of resolution. *American Journal of Ophthalmology, 46*, 102-113.

Wilkes, A. L. (1997). *Knowledge in Minds: Individual and Collective Processes in Cognition*. Hove, East Sussex: Psychology Press.

Wolford, G. (1975). Perturbation model for letter identification. *Psychological Review, 82*(3), 184-199.

Wolford, G., & Chambers, L. (1983). Lateral masking as a function of spacing. *Perception and Psychophysics, 33*(2), 129-138.

Wolford, G., & Hollingsworth, S. (1974). Lateral masking in visual information processing. *Perception & Psychophysics, 16*, 315-320.

Wolford, G., & Shum, K. H. (1980). Evidence for feature perturbations. *Perception & Psychophysics, 27*(5), 409-420.

Xing, J., & Heeger, D. J. (2000). Center-surround interactions in foveal and peripheral vision. *Vision Research, 40*, 3065–3072.

Yeshurun, Y., & Rashal, E. (2010). Precueing attention to the target location diminishes crowding and reduces the critical distance. *Journal of Vision, 10*(10).

Yu, D., Akau, M. M. U., & Chung, S. T. L. (2012). The mechanism of word crowding. *Vision Research, 52*, 61-69.

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