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 sensibly stated as saying that 'critical distance for crowding is about half the target's eccentricity'. 2) Crowding is predominantly a peripheral phenomenon. 3) Crowding increases strongly and steadily with eccentricity (as does the minimal angle of resolution, MAR). 4) Crowding is asymmetric as Bouma (1970) has shown. 5) For the inward-outward asymmetry the more peripheral flanker is the more important one. 6) Critical crowding distance corresponds to a constant cortical distance in primary visual areas like V1. 7) Except for Bouma (1970), crowding research mostly started in the 2000s. I propose the answer is 'no!' or 'not really' to most all of these questions. So should we care? I think we should, before we write the textbooks for the next generation.

Introduction

In 1962, the ophthalmologists James Stuart and Hermann Burian published a study on amblyopia where they 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 probably 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 here, i.e. has nothing to do with acuity or resolution in the visual field. Note further that any theory that is based on local, longitudinal processing only, invoking simple vs. complex receptive

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

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

[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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field types, rate of convergence/divergence and the like, will fail at explaining the phenomenon (today we know that crowding happens in the cortex). 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.

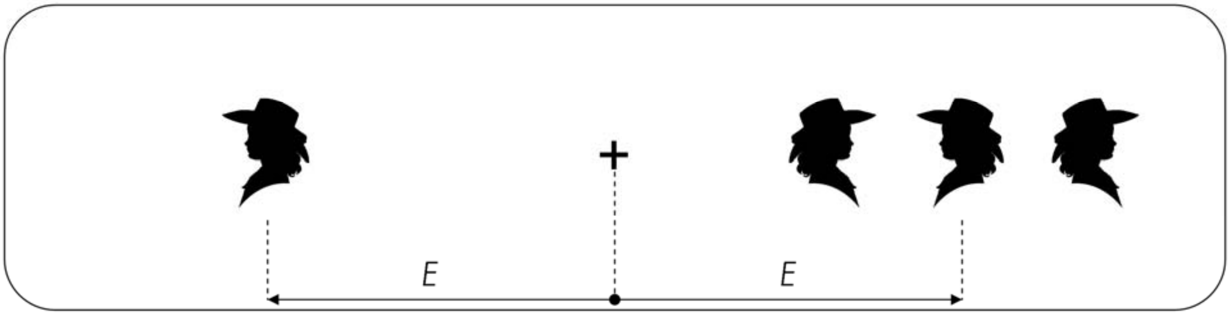

Figure 1. Simple demonstration of crowding. When fixating at the cross, the orientation for the hat on the left is seen but not that for the middle one on the right, even though the images are of the same size and at the same eccentricity. The phenomenon depends predominantly on eccentricity and pattern 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. Little knew the schools of thought of each other. By the time that we became interested in crowding (1988), there were twenty major papers on the subject, under a variety of keywords that more often than not took scarce notice of those of the other school. 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, 1985); myself, Ingo Rentschler and Lew Harvey studied character crowding at low contrast and we asked what mechanisms might underlie crowding (Strasburger, Harvey, & Rentschler, 1991a, 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 & 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, 2015b), 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

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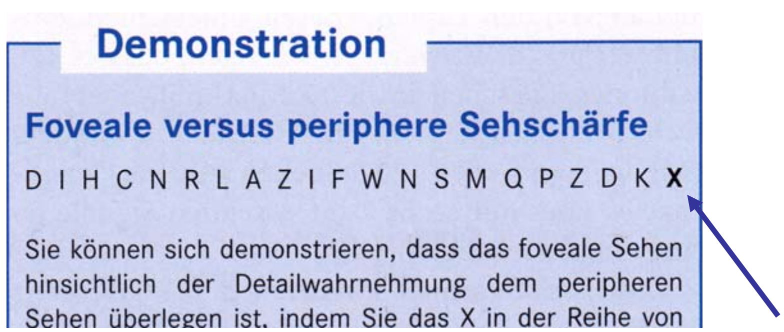
presents a trivialized dichotomy of parvo (*P*) and magno (*M*) systems in which the *P* system is supposedly specialized on pattern recognition because of its high resolution and small receptive fields. Thomas Kuhn in *The Structure of Scientific Revolutions* (Kuhn, 1962) explains that research traditions 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. My favourite for covering all the senses is Goldstein's well-known *Sensation and Perception*. Many chapters in it are on my list of required reading for my students. Yet it says nothing about crowding, whereas acuity, cortical magnification, and peripheral vision are all covered. 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 well-known vision scientists (see Figure 2). My other favourite, *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. 113–117) 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 7b, below, with a caption[4] that warrants understanding why it is wrong).


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

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

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Thus, either crowding is after all much less important for vision in general than I 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, 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 simple beliefs that, upon more scrutiny, turn out to be misleading or just wrong. They 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 myths, e.g. the myth (or the hope?) that two mechanisms will eventually explain crowding (many authors including myself invoke two mechanisms; they are just rarely the same two). I simply stopped after seven points. The paper is the fourth in a series of – slightly pointed – *myths* presentations in vision research (Strasburger, 2017b; Bach, 2017; Strasburger, 2017a; Strasburger, 2018b, *Preprint)*, and I trust more will follow[5].

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).

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

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

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crowding are connected subjects.

In medias res – one would agree with the following seven statements (one in each section) – or wouldn't one?

On Bouma's law

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

Bouma's law governs how crowding depends on the flankers' distance to the target. Before we come to that, though, it needs to be said what Bouma's law is *not*. This is to avoid a possible misunderstanding (perhaps another myth): Bouma's law is *not* a descriptor for crowding in general. That is even though Bouma's law is amazingly robust and general in describing a large variety of basic crowding situations, with letters, numerals, Landolt rings etc. amidst many kinds of flankers in various numbers and orientations. The reason that it is not a general descriptor is that crowding, as a phenomenon of pattern recognition, 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 often more than the sum of its parts. So, as indicated above, the proven and tested concept of simplifying by analytical dissection leads astray for crowding, and the isolated crowding stimulus – like the one in Figure 1 or Figure 4A – does 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, Rentschler, & Jüttner, 2011, Fig. 19, respectively), and has more recently been explored systematically 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). The message might be summarized as saying that "appearance (i.e., how stimuli look) is a good predictor for crowding" (Herzog et al., 2015).

That 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 merely changed in complicated ways that are not yet understood. Thus, in my mind grouping does not invalidate Bouma's law; I find that unlikely in light of the many situations in which it holds up well. It does, however, necessitate clarifying how Gestalt mechanisms interact with the local situation and thereby modify Bouma's law. Obvious explanations like "only the nearest flanker counts" have been shown not to work.

What follows here in the paper is about the isolated crowding task. Now that that possible misunderstanding about its universality is out of the way, we can get back to Bouma's law. The statement in the header sounds sensible enough and might suffice as a rule-of-thumb. We can do better, however. The amazing robustness and generality across configurations of that rule suggests there is something more fundamental about it. For a while now, we call it a law rather than a mere rule, equal in rank to other laws of psychophysics like Weber's law, Riccó's law, Bloch's law, etc. Now the requirements for a law as, e.g., standardly applied in classical physics are higher. Not only should the mathematical description of a "real-world" dependency fit the empirical data, it must crucially also fulfill certain a-priori, theoretical constraints: namely to make sense for the obvious cases, i.e. 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. This is where the formulation in the header fails.

The crucial point in the header statement is the qualifier *about*. 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, while the linearity holds for almost all visual tasks. There is a more important slur, however, a limitation of the rule's generality. It becomes apparent when considering the particularly important case for crowding: foveal vision and reading. The eccentricity angles (φ) are small there and the precise meaning of critical distance becomes important. Bouma (1970a) specified *d* as the threshold of internal or empty space between target and flankers; today's authors often prefer to specify flanker distance as measured centre-to-centre, for various reasons (Figure 4).

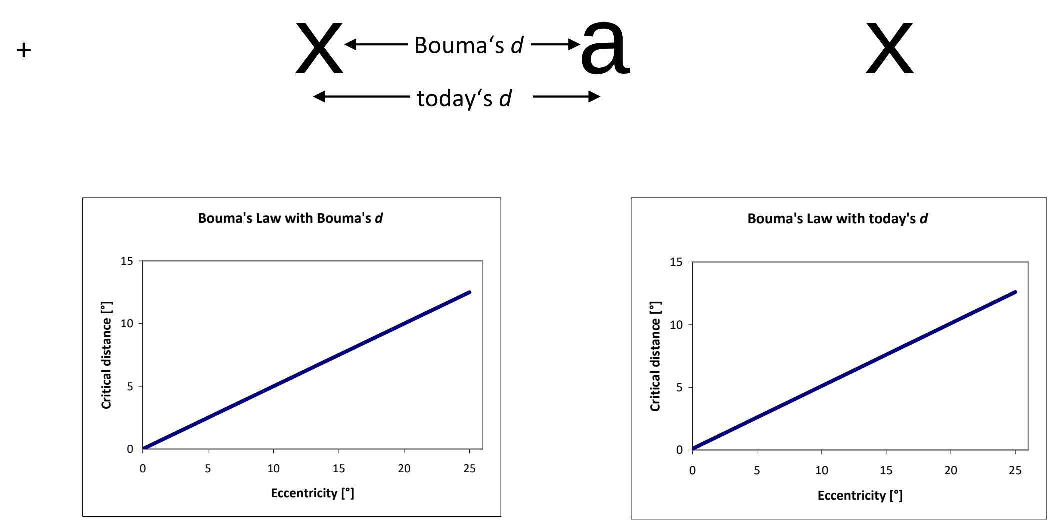

Figure 4. Top: Bouma's crowding stimulus arrangement. On the left is a fixation point (+), to the right of which a target letter (a) appears that is surrounded by two equally-spaced flankers (x). Target and flankers are in Times-Roman font, with a variable number of fixed-width spaces in between. Bottom: 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).

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,

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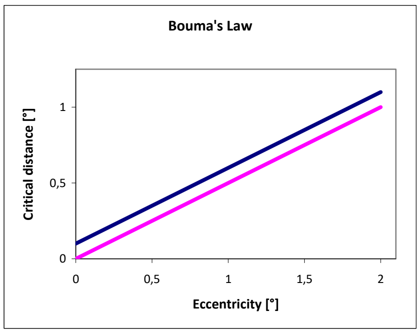
critical distance is *proportional* to eccentricity (pink line in Figure 5a). With the centre-to-centre definition, in contrast, critical distance is *not* proportional to eccentricity; it is just a little bigger, by one letter width. The difference is seen in Figure 5a, where the blue line is shifted relative to the pink line. The blue line has a positive axis intercept and represents a linear law, not proportionality. With the centre-to-centre definition in eq. (1) the stimulus configuration would become ridiculous in the centre fovea: proportionality would imply that target and flankers are at the identical location in the centre; just off the centre, target and flankers would overlap, as shown in Figure 4b. Importantly, it is *not* what Bouma said.



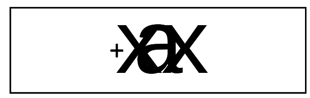


Figure 5. (a) Comparison of Bouma's law with critical distance defined as empty space (pink) vs. centre-to-centre (blue). (b) An absurd stimulus configuration that would result from an incorrect statement of Bouma's law.

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

$$d = 0.5\varphi + w, \tag{2}$$

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

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

Crowding and peripheral vision

Misconception 2). Crowding is predominantly a peripheral phenomenon. – **No**.

Crowding is of course highly important in the visual periphery. It is often even said to be *the* characteristic of peripheral vision (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, since, there, it is the bottleneck for reading and pattern recognition. Pelli and coworkers have pointed that out most explicitly (Pelli et al., 2007; Pelli & Tillman, 2008). Beware in that context that the fovea is much larger than one is mostly aware of: its diameter is around 5.2 deg visual angle (Polyak, 1941, Wandell, 1995). Note also that ophthalmologists appear to use the terms differently, referring to the 5.2° area as the macula lutea even though the anatomical macula is even much larger, estimated at 17° diameter by Polyak.) When vision scientists speak of 'foveal vision' or of 'the fovea' they are typically not referring to the foveal area but are

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talking about the situation where the observer fixates; i.e., they refer to the foveola (about 1.4° diameter) or indeed to the point of highest receptor density, the very centre. Note in that context that this maximum is reached only in an area of about 8–16 arcmin diameter (Li, Tiruveedhula, & Roorda, 2010, Fig. 6[6]), and that the point of fixation (i.e. the preferred retinal locus; PRL) is 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 about half a minute of arc is resolved.

In the rest of the fovea, acuity as we all know is much lower. Phrased differently, resolving Landolt gaps is not of foremost interest for reading. Letter sizes in normal reading far exceed the acuity limit. In normal reading, about one word fits into the fovea; so with an average length of roundabout five letters the letter width is about half a degree – more than 30 times the acuity limit.

Within the fovea, crowding is 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 that lateral interactions occur in the very centre is now well established (Flom, Weymouth, & Kahneman, 1963; 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. 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, Harvey, & Rentschler, 1991b, Pelli, Palomares, & Majaj, 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 in the very centre we might have standard crowding[7].

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.

[6] For conversion: 3.43 deg/mm (cf. Le Grand, 1968, p. 50)

[7] 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.

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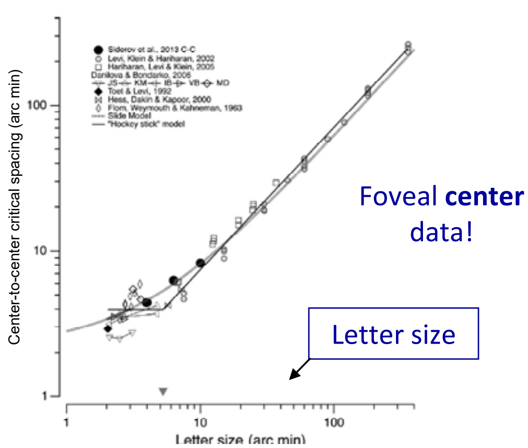
Yet that statement appears to me as rephrasing the independence of target size in the centre, up to 5′ size.

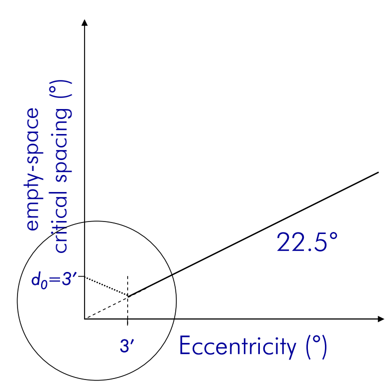
Above 5′ letter size, critical spacing is proportional to target size according to the hockey stick model. Now note that, by definition, that spacing is adjacent to the target, and, with increasing target size, its centreward border will move outward at a rate of half the target size (because the target 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′)[8], 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 thus 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[9] 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.





[8] 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.

[9] Calculated for a 0.5′ target and a 5′ target, with the bar at 4′ as in Figure 6a

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 visual field centre.

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

Crowding across eccentricity

Misconception 3). Crowding increases drastically and steadily with eccentricity, just like acuity decreases. – **Yes, no,** and **no**.

These are three questions in one. Let us consider acuity first: Common wisdom has it that it decreases strongly towards the periphery and this is how it is typically shown in textbook illustrations. Well, it does indeed decrease, i.e. the minimal angle of resolution (MAR) increases, but that happens only moderately. The myth of a steep incline – reproduced in most every textbook that mentions the periphery is based on the famous demonstration charts by Anstis (1974). There are three charts in that paper that illustrate the change of scale across the visual field, brought about by cortical magnification (Figs. 2, 3, and 4, reproduced here in Figure 7). The actual enlargement of peripheral letter size to accommodate cortical magnification is shown in Anstis's Fig. 2 (Figure 7a). However, since the letters are approximately at the acuity limit in that chart and are thus hard to recognize, Anstis enlarged the letters tenfold in his Fig. 3 (here Figure 7b), 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. 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 arises because the chart is mostly interpreted too literally (which Anstis probably never intended). It is a good example of how pictures can lead us wildly astray.

Figure 7. Figs. 2, 3, and 4 in Anstis (1974) illustrating cortical magnification. Letter sizes according to an estimate of the cortical magnification factor (left). Letters shown at tenfold increased size (middle). Same letter sizes but more letters added, to increase crowding (right).

But there is more. Anstis's Fig. 3 (here Figure 7b) 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 spaces one needs to look at instead. 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, after all, thus 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, assume an E_2 value of 1° for Landolt acuity (Strasburger et al., 2011, Table 4) and acuity of 1.0, 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 gap-size vs. eccentricity (Strasburger et al., 2011, eq. 8). In other words, we have a typical increase of roughly 2% for the MAR, which is really moderate indeed.

Anstis's third chart (Fig. 5, shown in Figure 7c) is an illustration of crowding. That one 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 the large letters might lead one to believe that these sizes are what peripheral vision needs. So the reader might wonder what, precisely, the graph shows.

Now to the question how crowding increases with eccentricity. The increase 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 8, which shows Bouma's law from Figure 4a together with the MAR (dashed line), from Anstis (1974, Fig. 1).

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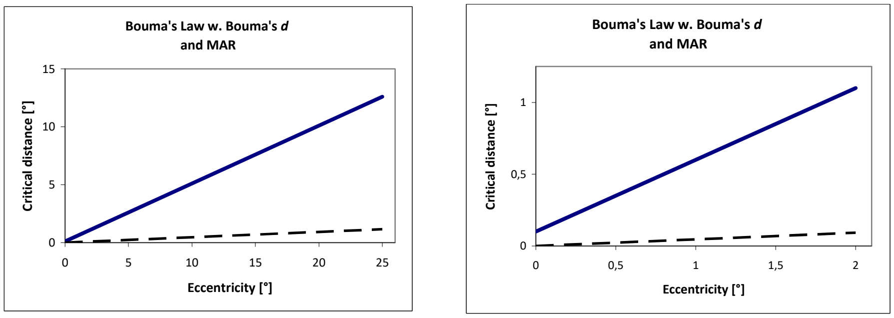

Figure 8. Bouma's law (continuous line, as in Figure 3a), compared to the increase of the MAR with eccentricity (dashed line; data from Anstis, 1974, Fig. 1). The graph is shown at two scales (as in Figure 4 vs. 5), to illustrate that at a large scale the slope difference matters most whereas at a small scale the intercept difference is more important.

Note, however, that in a sense we are comparing apples to oranges here, because, for crowding's critical distance, target size does not matter much, whereas for the MAR, target size not only matters but *is itself* the measure.

Moreover, that steep increase shown in the figure is that of crowding's critical distance, it is not that of crowding itself. Crowding, by its standard definition, is the *reduction of recognition performance* brought about by the presence of flankers. It is thus measured along a different dimension (percent correct) and for a comparison we need to convert *critical distance* to *recognition performance*.

To do that we require the psychometric function of letter recognition vs. flanker distance. It is surprisingly difficult to find data for that in the crowding literature, even though it is basic for letter crowding. For the present purpose I chose data from Yeshurun & Rashal (2010, shown in Figure 9a, red line) that were collected there 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 9b and 9c 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).

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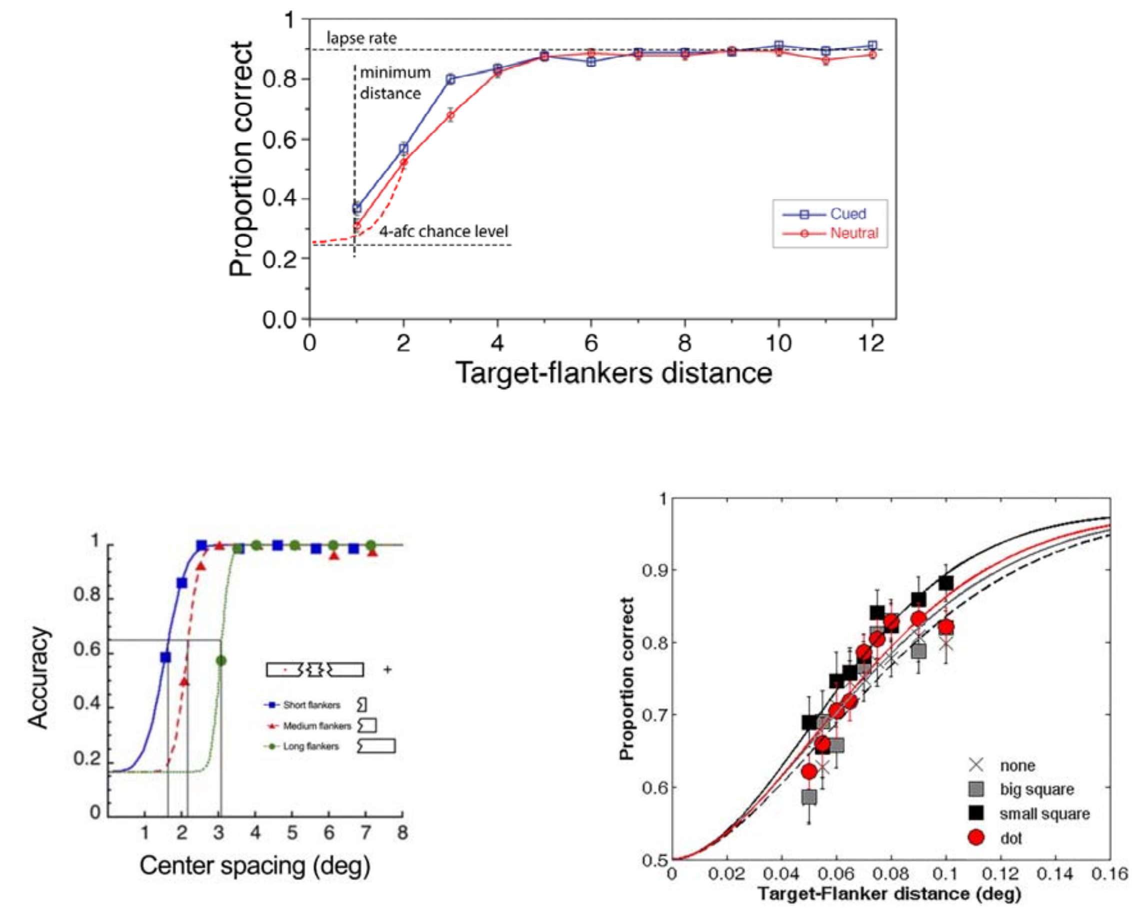

Figure 9. Psychometric functions vs. flanker distance. (a) For letter-T recognition (red line; disregard the blue line). Modified from Yeshurun & Rashal (2010, Fig. 5); (b) Example from Pelli's lab with novel patterns that allow widening the flankers (Rosen et al., 2014, Fig. 9a); the inset shows the stimulus and the legend. (c) Another recent example, used for quantifying spatial attention (Albonico et al., 2018, Fig. 4).

Now, from that psychometric function (p_c vs. flanker distance), together with Bouma's law (which describes critical distance vs. eccentricity), we can infer how crowding behaves with increasing eccentricity. Note first that, for a general answer to that question, distances between objects can be assumed as being, on average, independent of visual eccentricity ("the scene does not care where an observer looks at", so to say). Examples where that is approximately the case would be letters on a printed page, or people in a crowd. We further assume that, in the direction where we look, that distance is below the critical crowding distance, so that recognition is unaffected by crowding. Performance p_c is then at 100% minus the lapse rate λ (top right in Figure 9). Figure 10a 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–λ 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 $1 - \lambda - p_c$.

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The reduction is shown (in the upward direction) in Figure 10b. The figure is obtained from Figure 10a by re-scaling the y-axis and flipping the graph horizontally and vertically, so that crowding (the downward arrow in Fig. 10a) goes upwards, and flanker distance *d* goes backwards. The y-axis now shows crowding, as standardly defined.

Finally, observe that Figure 10b 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 9 or Figure 10b 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., d_c going backwards), centred at the mean object distance *d* (as in Figure 10b). 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 10b.

For an intuitive understanding inspect Figure 10b 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 but recognition performance stays unaffected because critical distance is below the objects' distance. However, at some eccentricity (shown as a dashed line), critical distance becomes equal and then larger than the distance between the objects in the scene. Crowding increases rapidly there, according to a sigmoid psychometric function like that in Figure 9 or 10a. A little further out in the visual field, behaviour is limited by chance performance and does not change further.

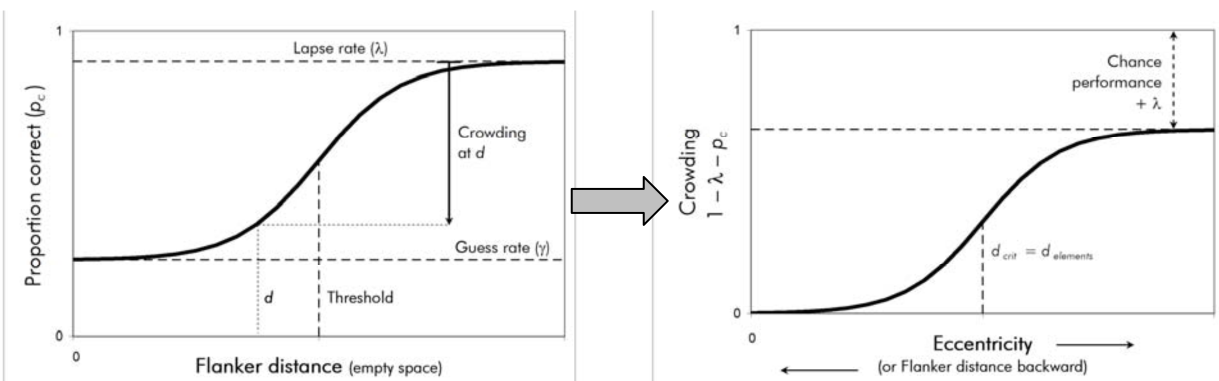

Figure 10. Schematic depiction of crowding, as defined standardly, i.e. as the impairment of recognition performance by the presence of flankers. (a) Psychometric function for proportion-correct performance in

a crowding task, as in Figure 9. The effect of crowding, at some flanker distance *d*, is seen as the downward arrow on the right, starting from best performance (1–λ). (b) Crowding as in figure part a, as a function of eccentricity.

So, back to the initial question: Does crowding increase strongly and steadily with eccentricity? Yes and no. Up to some (small) eccentricity, there is no crowding at all in most scenes. A little further out, there is full crowding (Figure 10b). And how does the increase of crowding compare with the increase of MAR? Put that way, there is no answer to that question because the MAR and the crowding effect are measured on different dimensions (stimulus size vs. proportion correct). Yet if we compare the crowding effect to the *effect of* the MAR (on visibility), crowding overrides the latter by far.

Crowding asymmetry

Misconception 4). Crowding is asymmetric with respect to the inward vs. outward flanker, as Bouma (1970) has shown. – **Yes** and **No**.

Crowding is asymmetric, as is well known, with the flankers outward *in the visual field* playing a different role than the more inward ones. Yet people like to cite Bouma's (1970) paper 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 notes it only as an aside at the end of the letter. The credit must go to Norman Mackworth (1965) instead: He reported the asymmetry several years earlier and it is he to whom Bouma refers (both in his 1970 and his 1973 paper) (Figure 11).

Mackworth (1965):

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

Bouma (1970):

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

Figure 11. 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

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refers to in it – and which is separate from the asymmetry that we are concerned with here – is shown in Figure 12 (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 was best, followed successively by the more inward ones. Word length was about 7.6° visual angle, so letter width was around 0.6° and the location of the first and last letter at about 3.5° eccentricity. Thus, already in these early experiments, the influence of eccentricity (i.e. reduced acuity) was shown to be 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) (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 11 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, and quite a few more). 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).

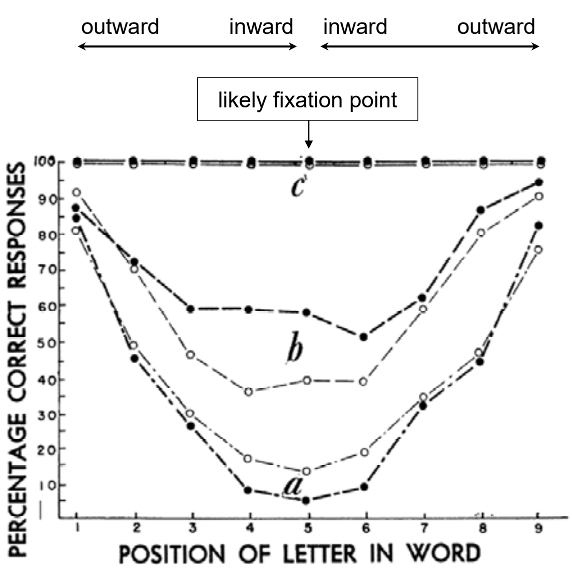

Figure 12. The end-of-the-line effect to which Mackworth (1965) refers (Haslerud & Clark, 1957). Letter recognition in 7.6°-wide nine-letter words. Open symbols: women; filled: men. *a:* fragmentary responses; *b:* incorrect; *c:* correct. Note that both the last and the first letter are *outside* in the visual field.

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

There appears to be wide agreement now that in the central-peripheral asymmetry (inward/outward in the visual field), the more peripheral flanker exerts more "adverse

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interaction" than the more central one (as Bouma, 1970, has put it)[10]. Bouma thus suggests that "the area of interaction is […] egg-shaped towards the retinal periphery", and this fits together well with the interaction zones drawn by Toet & Levi (1992).

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

An opposite asymmetry was further reported more recently by Strasburger & Malania (2013), with an informal model for explanation in Strasburger (2014). The data there (shown in Figure 13a) 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, that difference depended on eccentricity; it increased for the inward, but not the outward, flanker. Note that, since whole-letter confusions are not the only reason for crowding, such a result does not contradict a stronger net inhibitory effect of the more peripheral flanker under suitable conditions.

Several 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 that "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 (Petrov, Popple, & McKee, 2007; Petrov & Meleshkevich, 2011). 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 considered in the crowding literature: *feature binding* (von der Malsburg, 1981, Wolfe & Cave, 1999). According to hitherto proposed accounts for explaining crowding, like Wolford's (1975) classical feature-perturbation model, or modern statistically constrained pooling theories (Freeman, Chakravarthi, & Pelli, 2012, Balas, Nakano, & Rosenholtz, 2009, Keshvari & Rosenholtz, 2013), flanker attributes get mixed in with the target letter in the crowding task, such leading to "false" percepts. Such models do not (up to now) distinguish between (erroneously attributed) individual features, and (confusions with) whole characters. Yet there is quite a bit of evidence that whole-letter confusions are not just the sum of feature misallocations (Estes et al., 1976, Wolford & Shum, 1980, Strasburger et al., 1991; Huckauf & Heller, 2002, Chung, Legge, & Ortiz,

[10] If that sounds like a specialised question, note that it clashes with our understanding of the organisation of the visual field.

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2003, Strasburger, 2005, Vul, Hanus, & Kanwisher, 2009, Strasburger & Malania, 2013). This is where I suggest the concept of binding comes in. Whichever way implemented, it is an algorithm, or system characteristic, that decides which features belong together and which do not. The proposal is now that such feature binding *decreases with visual eccentricity*. Inward flankers would thereby be more "stable" and tend to interfere as a whole, whereas peripheral flankers would tend to mix-in features with the target (Figure 13b).

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 also 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.[11]

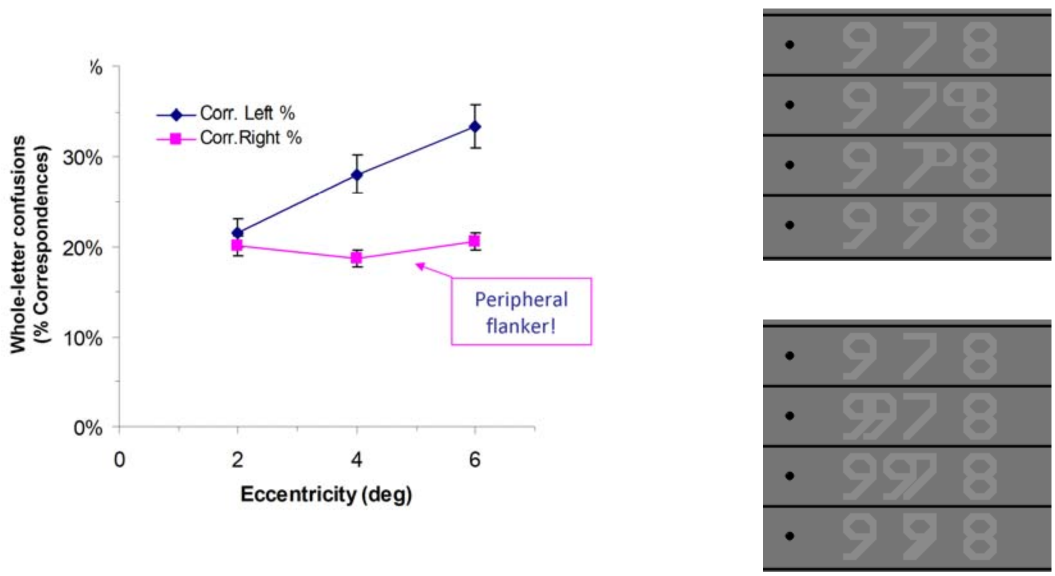

Figure13. (a) Reverse asymmetry in a crowding task reported in Strasburger & Malania, (2013, Fig. 8a) (modified). Confusions with the more central, but not the more peripheral, flanker depend on eccentricity. (b) Cartoon, as a memory hook for the mechanisms: (top) A peripheral letter part moving inward; (bottom) The more central flanker moving outward.

So in sum, neither of the flanking letters is just more "important" for 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. – **Not in the fovea**.

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

[11] A (symmetric) model of word recognition that very successfully treats location errors and identification errors separately (but not asymmetric binding that would contribute to identity errors) was recently presented by Bernard & Castet (2019). To quote form 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. And crowding is about how objects are spatially arranged *in the visual field* and how close they are. Now, the primary cortical visual cortex is retinotopically organized, so that that spatial arrangement translates to the primary cortex (and later areas) and how close the objects' representations are there. The question that then naturally arises is how the critical distances for crowding in the visual field translate to the distances in the cortical map(s). Thus, what is the equivalent of Bouma's law in the primary visual cortex?

Motter & Simoni (2007) proposed Bouma's law translates to a *constant* critical distance on the cortical map. Pelli (2008) presented a mathematical derivation of that constancy, based on Schwartz's (1980) logarithmic cortical mapping rule, and Nandy & Tjan (2012, p. 465) 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 posed above is of interest for our understanding of cortical architecture but is also of practical use for research, and Mareschal, Morgan, & Solomon (2010) applied that rule to their question and analysis. A different, non-constant rule was derived in (Strasburger et al., 2011).

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 he warns against this limitation).

A corrected rule that includes the fovea is presented in Strasburger (2017c, 2018a), shown in Figure 14 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, for example, MAR) is doubled (Levi, Klein, & Aitsebaomo, 1984, Strasburger et al., 2011; see Footnote 2 above). The newly proposed parameter d_2 is its 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

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

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

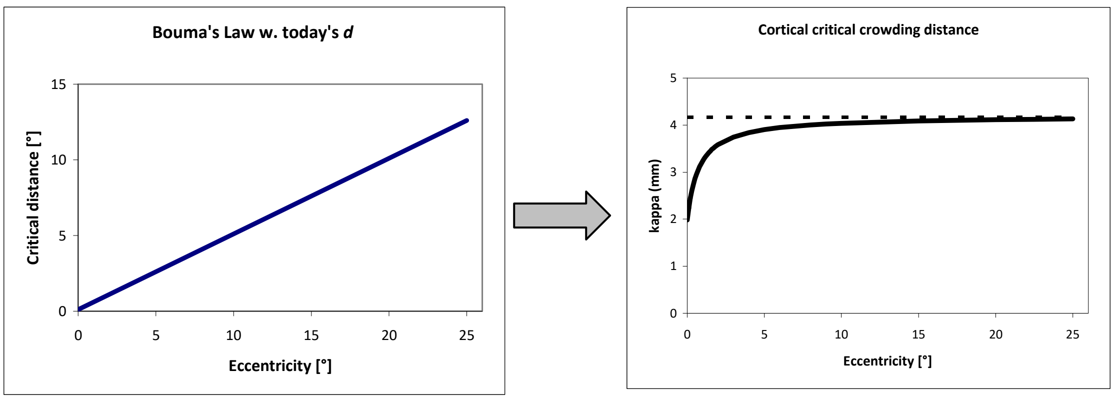

Figure 14. (a) Bouma's law in the visual field and (b) its cortical equivalent, i.e. how it translates to the cortical map in a primary visual area (Strasburger, 2017c, Strasburger, 2018a).

The graph of eq. (8) is shown in Figure 14b. Critical distance for crowding on the cortical map starts at some value in the centre (i.e. at $E = 0°$), and then – depending on the ratio $E_2/\hat{E}_2$ (the ratio of the respective E_2 values for MAR and crowding) – quickly increases to a different value that it reaches asymptotically. Constancy is thus reached above some eccentricity value, probably somewhere just outside the fovea. This equation can thus be seen as a generalization of Pelli's result which now also covers the case of central vision and reading.

Crowding research

Misconception 7). Except for Bouma's (1970) paper, crowding research mostly started in the 2000s. – (Not really.)

Crowding is 'quite the rage' in vision research these days; a very modern enterprise it is. Agreed, this is 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., 1991b).

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 as 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 terms in standard search machines.

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

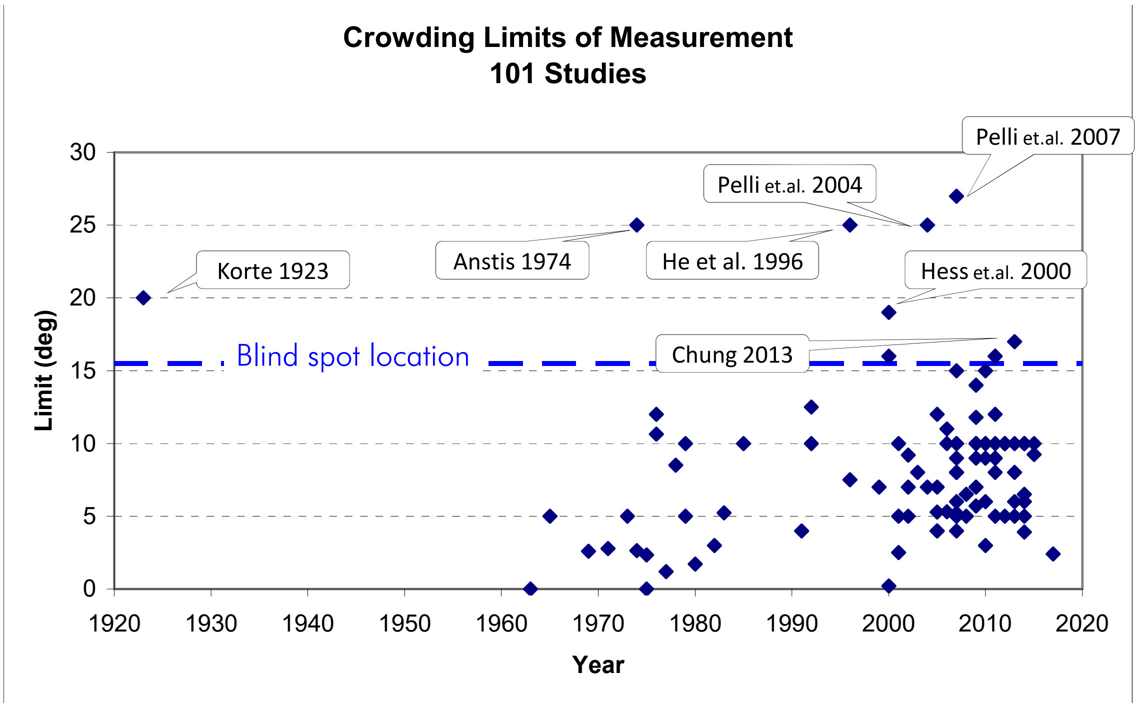

Figure 15. Essential crowding literature from 1923 to 2004. Abscissa: year of publication; ordinate: eccentricity in the visual field up to which crowding was studied in the paper. (References in Figure 16.)

Figure 15 shows a chart of crowding literature up to the present. Beware it is by no means complete. The x-axis shows the year of publication and the y-axis the maximum eccentricity (on a meridian or in the visual field) up to which data were reported. The horizontal dashed line at 15.5° marks the blind spot as a reference (Rohrschneider, 2004).

There are four points I wish to make: (1) The vast majority of studies are concerned with quite

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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 have no data). Filling the gap might need more digging in the older literature. Another reason fro that break, however, could be the expulsion of Gestalt psychologists from Germany, who were those interested in visual phenomena at that time.

Figure 16 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 16. Crowding literature from 1923 to 2004 shown in Figure 15. 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 was the first documented use of the term *crowding*; the Gestalt psychologist Wilhelm Korte was the first who provided an analysis of phenomena in indirect

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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 17a, 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 Alhazen’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 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 that was missing for an experimental unveiling of crowding was a direct comparison with single letters at the same eccentric location, which he could have easily done with his apparatus.

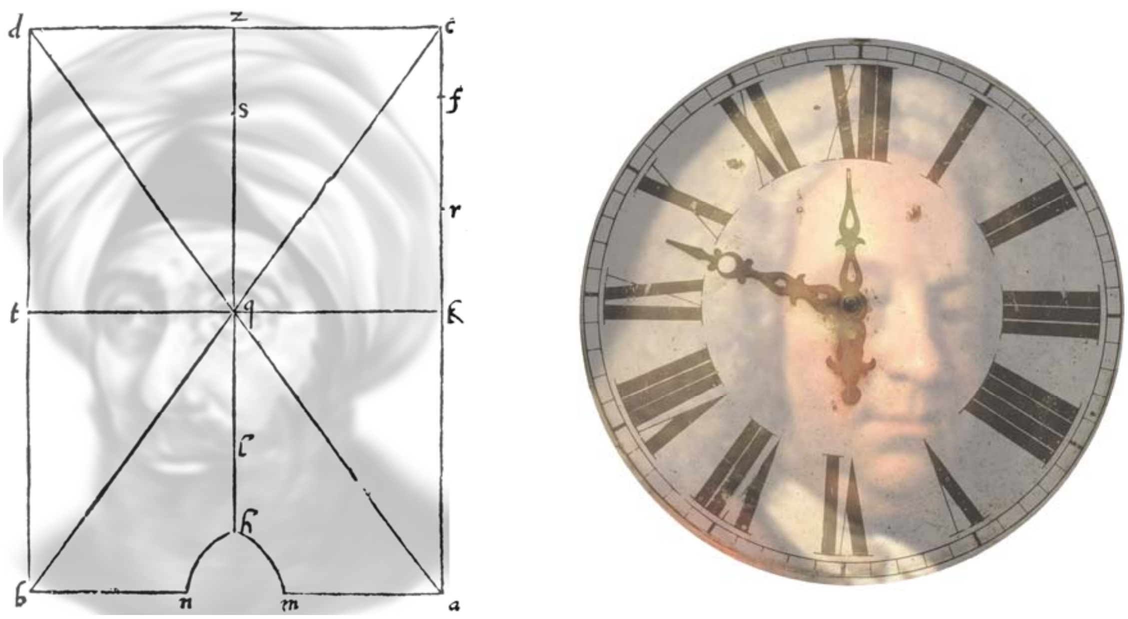

Figure 17. (a) Portrait of Ibn al-Haytham (c. 965 – c. 1040), with his perimeter superimposed (from Strasburger & Wade, 2015b). (b) Portrait of James Jurin (1684 – 1750) with a clock face, as described in his text and common at the time, superimposed. Note that the number Four is not in correct roman notation, so crowding will have been more prominent (from Strasburger & Wade, 2015a; both artworks by Nicholas J. Wade, 2015).

A second example for close misses is James Jurin’s *An essay on distinct and indistinct vision* (1738; Strasburger & Wade, 2015a, Figure 17b):

> “The more compounded any object is, or the more parts it consists of, it will, ceteris paribus, be more

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> 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:

> ''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 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[12]. 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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[12] Is there a Weber-Fechner law? Or is that a *textbook duck*? Which term is correct: "chi-squared" or "chi-square"?

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