METHOD ARTICLE

A clinical test for visual crowding [version 1; referees: 2 approved with reservations]

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Abstract

Crowding is a major limitation of visual perception. Because of crowding, a simple object, like a letter, can only be recognized if clutter is a certain *critical spacing* away. Crowding is only weakly associated with acuity. The critical spacing of crowding is lowest in the normal fovea, and grows with increasing eccentricity in peripheral vision. Foveal crowding is more prominent in certain patient groups, including those with strabismic amblyopia and apperceptive agnosia. Crowding may lessen with age during childhood as reading speed increases. The range of crowding predicts much of the slowness of reading in children with developmental dyslexia. There is tantalizing evidence suggesting that the critical spacing of crowding indicates neural density (participating neurons per square deg) in the visual cortex. Thus, for basic and applied reasons, it would be very interesting to measure foveal crowding clinically in children and adults with normal and impaired vision, and to track the development of crowding during childhood. While many labs routinely measure peripheral crowding as part of their basic research in visual perception, current tests are not well suited to routine clinical testing because they take too much time, require good fixation, and are mostly not applicable to foveal vision. Here we report a new test for clinical measurement of crowding in the fovea. It is quick and accurate, works well with children and adults, and we expect it to work well with dementia patients as well. The task is to identify a numerical digit, 1-9, using a new “Pelli” font that is identifiable at tiny width (0.02 deg, about 1 minarc, in normal adult fovea). This allows quick measurement of the very small (0.05 deg) critical spacing in the normal adult fovea, as well as with other groups that have higher critical spacing. Preliminary results from healthy adults and children are presented.

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Referee Status: ? ?

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Introduction

Crowding is a major limitation of visual perception. Because of crowding, a simple object, like a letter, can only be recognized if clutter is a certain *critical spacing* away (Bouma, 1970; Levi, 2008; Pelli & Tillman, 2008). That needed spacing grows linearly with eccentricity. In the fovea, we find the critical spacing of crowding to be about 0.05 deg in healthy adults, but it is much higher in certain clinical conditions, such as strabismic amblyopia and apperceptive agnosia (Song *et al.*, 2014; Strappini, Pelli, Di Pace, & Martelli, unpublished report). Even when text is scaled in proportion to eccentricity, peripheral reading is slow and may be a useful model for slow central reading (Latham & Whittaker, 1996; Legge *et al.*, 2001; Pelli *et al.*, 2007). There is some evidence that the critical spacing of crowding drops during childhood as reading speed increases (Kwon *et al.*, 2007; Pelli & Tillman, 2008). In shallow orthography languages, children with developmental dyslexia are doomed to read slowly relative to their peers and have an abnormally large critical spacing (Bouma & Legein, 1977; Martelli *et al.*, 2009; O'Brien *et al.*, 2005).

Crowding is only weakly associated with acuity; some patient groups have greatly worsened crowding with near normal acuity and others have greatly worsened acuity with near normal crowding (Song *et al.*, 2014). There is tantalizing evidence suggesting that the critical spacing of crowding indicates neural density (participating neurons per square deg) in the visual cortex (Strappini, Pelli, Di Pace, & Martelli, unpublished report). Similarly, crowding has been linked to reading speed in children and in patients, so it might be a useful assay of cortical health and development. Thus, for basic and applied reasons, it would be very interesting to measure foveal crowding clinically in children and adults with normal and impaired vision, and to track the development of crowding during childhood.

Three limits to legibility

In normal vision, letter acuity size A and the critical spacing of crowding $S_{crowding}$ both grow linearly with eccentricity φ (Levi *et al.*, 1985; Toet & Levi, 1992). Based on their measurements in the peripheral visual field, Song *et al.* (2014) provided these formulas:

$$A = 0.029\ (\varphi + 2.72\ \text{deg}), \tag{1}$$

$$S_{crowding} = 0.3\ (\varphi + 0.45\ \text{deg}) \tag{2}$$

They showed that a letter is recognized only if it respects three limits: acuity, crowding, and overlap masking. They found no interaction among the three limits. Overlap masking can be completely avoided by using a center-to-center spacing of at least 1.4 letter widths.

Isolating the crowding limit

To measure crowding with letters, the letters must be above the acuity limit, yet smaller than the critical spacing. This is easy to achieve in the periphery, where the critical spacing is much larger than the acuity. The ratio of critical spacing to acuity is

$$S_{crowding} / A = 0.3\ (\varphi + 0.45\ \text{deg}) / 0.029\ (\varphi + 2.72\ \text{deg}),$$
$$= 10.3\ (\varphi + 0.45\ \text{deg}) / (\varphi + 2.72\ \text{deg}), \tag{3}$$

At large eccentricity, beyond 3 deg, this ratio is large and asymptotically approaches a value of about 10:1. Most studies of crowding are done in the periphery with small targets that are above acuity yet much smaller than the critical spacing to be measured. At small eccentricities, in the fovea, this ratio is approximately 1.7:1. The critical spacing 0.14 deg (according to the formula) is less than twice the threshold size of 0.08 deg. In fact, our foveal measurements reveal a smaller critical spacing, less than 0.1 deg, which is impossible to measure with 0.14 deg letters without overlap. The fovea is the hardest place to measure crowding, but that is the site that is most affected by deficits like strabismic amblyopia and is also the site associated with highest neural density, so it seems worth the effort.

Despite this difficulty, there have been a number of reports of foveal crowding (Atkinson *et al.*, 1988; Atkinson *et al.*, 1986; Bedell *et al.*, 2013; Bedell *et al.*, 2015; Danilova & Bondarko, 2007; Hess *et al.*, 2000; Kwon *et al.*, 2007; Liu & Arditi, 2000; Malania *et al.*, 2007; Semenov *et al.*, 2000; Siderov *et al.*, 2013). The thinnest discriminable target, for this purpose, is the Vernier target (Malania *et al.*, 2007). Observers can detect a 0.01 deg misalignment of two thin lines in a Vernier target. However, binary discrimination is not an ideal clinical task because it yields information slowly. With two choices there is a high, 50%, chance of correctly guessing.

Least legible width: a contest

For faster testing, we wanted to use letter identification, with many possible letters, to minimize the guessing rate (Pelli & Robson, 1991). We needed a font that can be identified at a tiny width, a small fraction of the 0.05 deg critical spacing we seek to measure. We evaluated many fonts, and designed several of our own, to achieve a legible width approaching that of a vernier target. We call the new optotypes the "Pelli" font. It has a 5:1 aspect ratio and has a stroke width that is one half the letter width. The Sloan letters, much used in clinical testing, and designated as the standard optotypes for acuity testing in the USA, have a 1:1 aspect ratio and a stroke width of 1/5 the letter size (Sloan, 1959). Both fonts are displayed in Figure 1.

Figure 2 allows you to test your own eye. The figure is an acuity test chart, but this test is unusual in focusing exclusively on width. It measures the smallest legible width for three fonts. On each line, the letters of the several fonts have various heights, but they all have the same width. From left to right, the fonts are Pelli, Gotham (Condensed Light), and Sloan. The Gotham font, from Hoefler and Co. (http://www.typography.com), is a commercial font for general text setting, with some attention given to performing well at small sizes, e.g. in tables. It comes in a wide variety of styles including Narrow and Condensed, and, of those we tried, the "Condensed Light" style gave the smallest legible width of 0.04 deg. We also tested two other fonts that have been designed to perform well at small visual angles: Hoefler and Co. Retina Micro font, designed for stock price tables in the *Wall Street Journal* and Clearview Hwy 1-B, designed for highway signs and adopted as the standard in many US states.

Special populations

To test children as young as 4 years, we considered the use of popular pictograms, such as Lea Symbols and Patti Pics, used

Figure 1. Two fonts for vision testing. The new "Pelli" font has been designed to measure the spacing threshold. The Sloan font was designed by Louise Sloan to measure the size threshold, and has become the US standard for acuity testing (Sloan, 1959). (See Software availability.)

Figure 2. A contest for minimum legible width among three fonts: Pelli, Gotham Condensed Light, and Sloan. On each horizontal line of numbers and letters there are three fonts, and all characters in the line have the same width, though their heights vary greatly. The next line down is always smaller by a factor of $2^{-0.5}$ = 71%. Thus, going down two lines halves the letter size. The Sloan font, or optotype, is the USA standard for acuity testing. It has a 1:1 aspect ratio. Among the commercially available fonts that we tested, Gotham Condensed Light, with an aspect ratio 2.8:1, has the narrowest legible width. We created several experimental fonts (Arouet and Sticks, not shown) and finally created the "Pelli" font, which has the narrowest legible width. It has a 5:1 aspect ratio. Sloan's stroke is 1/5 its width; Pelli's stroke is 1/2 its width. In our sample of normally sighted adults, threshold width is about 0.02 deg for Pelli, 0.04 deg for Gotham (Condensed Light), and 0.05 deg for Sloan. You can use this chart to confirm this for your own eyes. At any viewing distance greater than 2 m, once you reach your limit for Sloan, you'll be able to read four more lines of the Pelli font.

for illiterate testing, but they seemed unlikely to yield the tiny threshold width we need (Mercer *et al.*, 2013). Thus, we decided to use numbers, anticipating that most children will have some familiarity. We gave each child a page with the 9 possible numbers so that they can respond by pointing instead of speaking if that seems easier. We've had good results from this with the several children we have tested so far.

The new test

The new test uses the digits 1–9, familiar to most children and patients. The 9 categories are sufficiently many to yield a low guessing rate (1/9) for fast threshold estimation. A new font, "Pelli", with no internal white space, designed for this test with help from Hannes Famira, a professional font designer, is legible down to very small width: 0.02 deg (1.2 minarc) in the normal adult fovea. In the same spirit as David Regan's repeat-letter acuity chart (Regan *et al.*, 1992), our test alternates two different target digits over the whole display. These two alternating targets crowd each other. As in Regan's chart, no matter where the observer's eye lands on the screen, a target will be imaged on the observer's fovea, so the test can accurately assess foveal function even in observers with poor fixation.

Figure 3 demonstrates the principle. There are two charts, one using the Pelli font, the other using the Sloan font. Each chart has two halves, left and right. These charts measure threshold spacing. Any given row has the same letter or number spacing (center to center), all the way across within each chart and across charts. The two halves of each chart have different character sizes. The ratio of spacing to size is 1.2 on the left and 1.8 on the right, on both charts. When you read down as far as you can go, you might be able to read farther down the left half because it has larger letters. The left-side letters are 1.8/1.2=1.5 times bigger, and the successive rows of the chart are approximately 1.4:1, so, if you are *size*-limited, you will read one line farther down on the left side. However, if you are *spacing*-limited, the bigger letters won't help. This left-right difference is diagnostic. The critical spacing is small, so in order to reach it, letters must be legible at very narrow width. Testing ourselves, we find no left-right difference in our limit of reading on the Pelli chart (left). We do find a one-line difference on the Sloan chart on

Figure 3. These charts allow you to measure your threshold spacing with two fonts, Pelli (left) and Sloan (right). The center-to-center letter or number spacing is fixed for each row, all the way across both charts. See text for details.

the right. Thus the Pelli font allows measurement of critical spacing in the healthy fovea, and the Sloan font does not.

In our new test, the QUEST adaptive procedure adjusts the spacing of each chart to efficiently estimate threshold spacing (Watson & Pelli, 1983). Size is proportional to spacing, usually with a 1.4:1 ratio of spacing to size. Once overlap masking has been avoided, a target letter is identifiable if and only if the target and flankers satisfy both the size limit of acuity and the spacing limit of crowding.

The observer is asked to identify both targets in each presentation, in any order, and each identification response counts as a trial, so each presentation yields two trials. In 20 trials (i.e. 10 presentations) QUEST achieves an accurate estimate of threshold. We present preliminary results showing that the measured threshold spacing is practically independent of the spacing-to-size ratio used to measure it.

In normally sighted adults, Regan's repeat-letter acuity chart yields the same acuity as a single-letter chart. That is perhaps surprising, since one might expect crowding. However, the studies reported by Pelli *et al.* (2004) included experiments showing that simple targets are not crowded by identical flankers, but that finding was not discussed in the paper. Presumably the flankers contribute the same features as the target, so combining features from both yields the same summary statistics as from the target alone, and thus identification is unaffected.

Methods

Visual testing

All stimuli are presented on a laptop screen. The observer sits at a long viewing distance (2 to 10 m) away from the display. We compute the minimum viewing distance to achieve at least 400 pixel/deg, so that a 0.02 deg letter will be at least 8 pixels wide. The minimum distance depends on the screen resolution of the particular laptop. The MATLAB formula is

```
minViewingDistanceCm=57*(minPix/letterDeg)/(screenWidthPix/
                                    screenWidthCm);          (4)
```

where letterDeg=0.02, minPix=8.

Our experiments ran in MATLAB 2015b with the Psychtoolbox 3.0.12 extensions on laptop computers running OS X or Windows (Kleiner *et al.*, 2007). The Psychtoolbox software is available, free (http://psychtoolbox.org). Our testing program is called *CriticalSpacing.m* (see Data and software availability). We are making it available, and hope this will encourage more investigators to measure the critical spacing of crowding.

When testing, we use a wireless keyboard to receive the observer's responses, since the screen is so far away. Each presentation is a static chart. We ask healthy adults to respond to each chart by typing the character (digit) corresponding to each of the one or two targets presented. Invalid keys are dead and are ignored. When a valid key is typed, it is echoed by computer speech, e.g. "3". Each correct response is followed by a faint beep. For each presentation, the scoring ignores the order of responses. The observer is informed that the two targets are always different, so that the observer must respond with two digits. Typing the same key again is ignored. After both target responses have been recorded, if testing a child, the computer randomly says, "Good", "Very good", or "Nice".

A green progress bar is always present on the right side of the screen and grows, after each presentation, from the bottom of the screen, reaching the top of the screen at the end of the run (usually 10 presentations). The computer says "Congratulations" at the end of the run. Figure 4 shows screenshots taken during testing.

The static presentation can have one of four configurations. Each measures a size or spacing threshold, using single or repeated targets.

SPACING OF REPEATED TARGETS	New! Two alternating targets repeated over the whole screen (Figure 4A).
SPACING OF SINGLE TARGET	Traditional. A single target surrounded by four flankers, left, right, up, and down. (Figure 4B) (Exception: For Figure 7, we used only two flankers, left and right.)
SIZE OF REPEATED TARGETS	The screen is divided into two halves, left and right (Figure 4C). Each half shows a single target, repeated to fill the space.
SIZE OF SINGLE TARGET	Traditional. A single target (Figure 4D).

In the REPEATED-TARGETS conditions there are two different targets; in the SINGLE-TARGET conditions there is one target. The observer is asked to report the targets. The chart is displayed until the observer has given a response for each target (one or two).

The display consists of characters all drawn at the same size from one font and alphabet. We are most interested in our new Pelli font, using "123456789" as possible targets, but we have also tested Sloan, using "DHKNORSVZ", and Gotham (Condensed Light), using "123456789". The entire run uses a single ratio of spacing to size, typically 1.4. QUEST (included in the Psychtoolbox) controls the size or spacing; the other parameter tracks it proportionally. QUEST reports horizontal size and spacing. When characters have an aspect ratio that is not 1:1, the spacing is proportional, i.e. vertical spacing is proportional to height and horizontal spacing is proportional to width.

On a REPEATED-TARGETS presentation, if the targets were repeated out to the edge of the display, the outermost targets would be exposed on one side and would be less crowded. Our instructions try to minimize this by asking observers to concentrate on the middle of the display. And our design prevents escape from crowding by using a non-informative "margin" character around the edge on every REPEATED-TARGETS presentation. When the alphabet is "DHKNORSVZ", we use "X" on the margin. When the alphabet is "123456789", we use "$" on the margin. This avoids problems with edge effects.

One target is at the center of the display, and other characters are added. In the SINGLE conditions, for SIZE, the target remains

alone; for SPACING, we add four random flankers (drawn randomly from the alphabet), left and right, up and down.

In the REPEATED-TARGETS condition, for SIZE, the screen is divided in two, left and right; each half has its own target. The target is repeated left and right and up and down to fill the display, except for the screen margin. For SPACING, the two targets alternate, left and right and up and down, to fill the whole display, except for the screen margins.

The threshold estimation procedure is like that used by Song *et al.* (2014). One parameter (horizontal size or spacing) is controlled by QUEST. The other parameter scales proportionally in a fixed ratio of spacing to size (Figure 5), which is usually 1.4:1, but we also tested other ratios QUEST assumes a Weibull function describing probability of threshold versus log size or spacing and estimates the threshold parameter alpha. The steepness parameter beta is set at 3.0. Each run is 20 trials. Presentations with repeated targets have two targets and thus count as two trials. Presentations with single targets yield just one trial. At the end of the run, the QUEST procedure provides an estimate of threshold.

Creating the Pelli font

To create the Pelli font, we made sketches on paper, which we viewed from a great distance and adjusted to enhance recognition. The sketches were then drawn in GraphicConverter and further adjusted. These pixel-based sketches were traced in RoboFont (Version 1.7). The descender was set to 0 units and x-height, ascender and cap height were set to 1000 units. All characters of this fixed pitch or monospaced font were set to a setwidth of 200 units, except that the space and non-breaking space characters

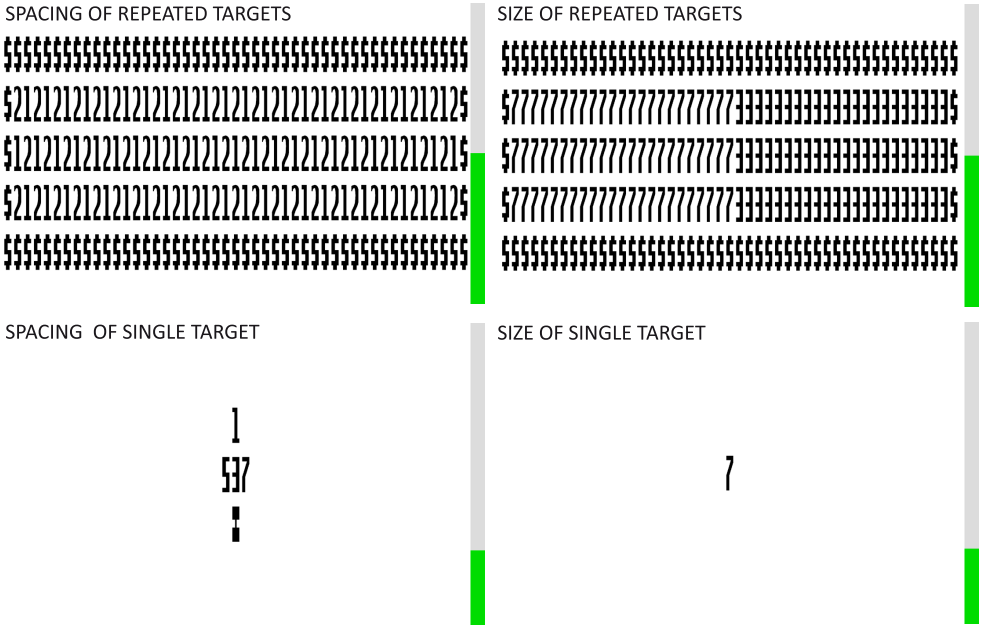

Figure 4. Four screenshots taken during testing, one for each kind of threshold measurement. The green bar at the right of each screenshot indicates progress through the run of 20 trials (ten presentations of repeated targets or 20 presentations of single targets). Threshold for spacing with repeated targets (left upper) and a single target (left below). Threshold for size with repeated targets (right upper) and with a single target (right below).

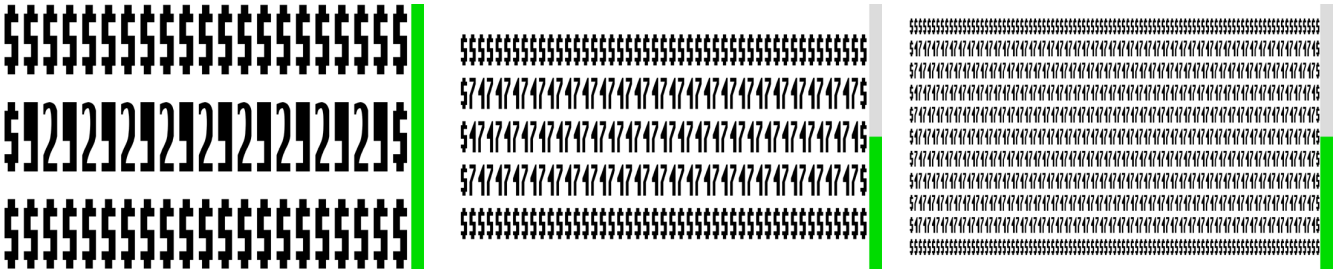

Figure 5. Screenshots at three different spacings of repeated targets.

were set to 100 units width. The resulting cubic outlines were generated into an OpenType font. See Data and software availability.

Results

Dataset 1. Several size thresholds (in deg) for each font listed

http://dx.doi.org/10.5256/f1000research.7835.d111930

Dataset 2. Threshold spacing of six observers at several values of spacingOverSize

http://dx.doi.org/10.5256/f1000research.7835.d111931

Dataset 3. 4 spacing thresholds for each of 2 conditions (single and repeated target) for each of two observers

http://dx.doi.org/10.5256/f1000research.7835.d111932

We measured threshold width for various fonts that have a reputation for legibility at small angular subtense (Figure 6). ClearviewHwy (www.clearviewhwy.com) is designed for highway signs, has been approved by the US government, and has been adopted by several states, including New York. Retina Micro was designed for typesetting stock price tables in the Wall Street Journal. Gotham (Hoefler & Co.) is an all-round font that comes in a wide range of styles including a very thin Compressed Light. These thresholds were all measured on one experienced healthy adult observer. Standard errors are about 5% of the plotted means. We are surprised by the cluster including Sloan near 0.05 deg. Only the Pelli font escapes to achieve a much smaller threshold size, of 0.02 deg for this observer, XW.

We measured threshold spacing with repeated targets with the Pelli font on 6 observers (O1–O4 four adults, C1–C2 two 8-year-old children, all healthy) at 3 spacing:size ratios: 1.2, 1.5, 1.8. We collected each threshold once (4 observers, U Rome-Martelli), twice (1 observer, NYU-Pelli-Qiu), or six times (1 observer, NYU-Pelli-Wu). For the latter two observers, we also collected the same number of threshold spacings with a single target.

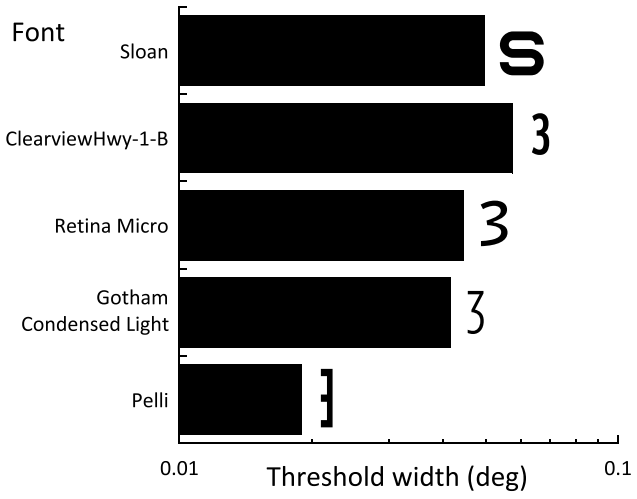

Figure 6. Threshold width of five fonts.

Figure 7 shows these threshold spacing for the Pelli font. Observers C1 and C2 are 8-year-old children; the rest are adults.

A single threshold measured by co-varying size and spacing might be hitting either a size or spacing limit. (Overlap masking is negligible at the large ratios of size to spacing that we used.) The hypothesis that the thresholds are *spacing* limited predicts that the spacing threshold will be *independent* of the spacing:size ratio. The hypothesis that the thresholds are *size* limited predicts that the spacing threshold will be *proportional* to the spacing:size ratio. Thus the two hypotheses predict that the measured spacing thresholds will have a log-log slope of 0 or 1, if they are spacing- or size-limited, respectively. We did linear regressions to estimate the log-log slope

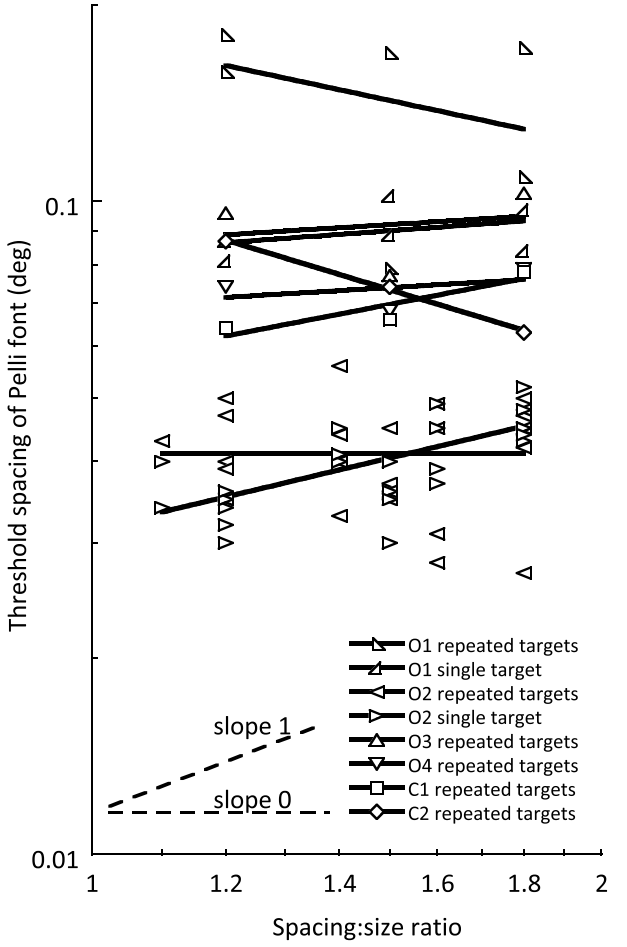

Figure 7. The critical spacing of crowding. Spacing thresholds were measured with the Pelli font. For each observer, we fit a linear regression line to each kind of threshold (single or repeated target) that was measured at several spacing:size ratio. The slopes are practically zero, showing that threshold spacing of each observer is conserved across this range of spacing-to-size ratio. This is consistent with spacing-limited threshold and inconsistent with the unit slope of a size limit.

of all the data for each of the 8 observers. Across all the observers the log-log slope mean±se is 0.02±0.17 which is insignificantly different from zero and about 6 standard errors below 1. This confirms that these spacing thresholds are spacing-, not size-, limited.

Threshold spacing mean±se was 0.065±0.006 (repeated target) and 0.049±0.004 (single target). This small difference (0.065 vs. 0.049 deg) is significant, about three standard errors. The slightly stronger crowding in the repeated-target condition is very likely because the repeated target was flanked on all four sides by other digits, whereas the single target was flanked only on left and right (the exception noted above in the SPACING & SIZE table.).

To better compare the repeated- and single-target estimates of threshold spacing *with flankers on all four sides*, we measured both 4 times on two observers (Table 1). The repeated-target thresholds are 9% higher.

Discussion

Neural density and crowding

Strappini, Pelli, Di Pace, and Martelli (unpublished report) note that the lesions in apperceptive agnosia are accidental and diverse, from which one might expect diverse effects. Instead they find that the known diversity of the apperceptive agnosic population is roughly accounted for by a one-parameter model: the critical spacing of crowding. Crowding limits vision in the periphery, in strabismic amblyopes, and in patients with apperceptive agnosia, making it urgent to know what drives crowding. Acuity does not. Song *et al.* (2014) report a double dissociation of acuity and crowding: apperceptive agnosia worsens crowding while sparing acuity, and anisometropic amblyopia worsens acuity while sparing crowding. This shows that acuity and crowding are functionally independent. So what drives crowding? Pelli (2008) shows that the critical spacing of crowding is a fixed distance on the cortical surface, 6 mm in V1. Perhaps the extent of crowding reflects the number of cortical neurons per deg^2 participating in the recognition task. This neural density may be reduced by lower cortical magnification (in the periphery), take over by the other eye (in strabismic amblyopia), or cell death (in agnosia).

Posterior Cortical Atrophy (PCA) is Alzheimer's disease occurring in the visual cortex, which is one etiology for apperceptive agnosia (Crutch, 2014). Crutch & Warrington (2007); Crutch & Warrington (2009) showed that the patients' reading difficulties are well described as crowding. In their study of crowding in 26 PCA patients, Yong *et al.* (2014) report a correlation between crowding and lower grey matter volume within the right collateral sulcus, between the fusiform and lingual gyri. With regard to neural density, crowding in the central vision of the agnosic patients might reflect limited plasticity of the ventral stream, i.e. insufficient recruitment of other neurons to entirely make up for the loss in neural density.

We will be using this new test to measure foveal crowding in children and adults, healthy and patients, to develop norms and evaluate the possibility that critical spacing might track neural density.

Table 1. Threshold spacing of single and repeated targets.
Each threshold was measured 4 times.

Observer	Repeated targets	Single target	Ratio repeated: single
O1	0.060±0.003 deg	0.055±0.002 deg	1.09
O2	0.076±0.006 deg	0.070±0.002 deg	1.09

Conclusion

The critical spacing of crowding in the fovea seems to be an important measure of visual function and cortical health. This new test is a good way to measure it.

Data and software availability

Data

F1000Research: Dataset 1. Several size thresholds (in deg) for each font listed, 10.5256/f1000research.7835.d111930 (Pelli *et al.*, 2016a).

F1000Research: Dataset 2. Threshold spacing of six observers at several values of spacingOverSize, 10.5256/f1000research.7835.d111931 (Pelli *et al.*, 2016b).

F1000Research: Dataset 3. 4 spacing thresholds for each of 2 conditions (single and repeated target) for each of two observers, 10.5256/f1000research.7835.d111932 (Pelli *et al.*, 2016c).

Software

The "Pelli" and Sloan fonts are available for noncommercial research use from GitHub: https://github.com/denispelli/Eye-Chart-Fonts/

The Sloan font file was created by Denis Pelli based on Louise Sloan's specifications and used for the Pelli-Robson contrast sensitivity chart (Pelli *et al.*, 1988). Louise Sloan's design has been designated the US standard for acuity testing by the National Academy of Sciences, National Research Council, Committee on Vision (NAS-NRC, 1980). The C is a Landolt C. The C and O are particularly hard to discriminate from each other, so Elliott *et al.* (1990) recommend that most studies omit the C, as we did here.

CriticalSpacing.m is our MATLAB program that uses any font to measure acuity and critical spacing. It allows testing with single or repeated targets. With single targets, it can test at any eccentricity, using brief presentation. We are making it available here, and hope this will encourage more investigators to measure the critical spacing of crowding. If you publish results collected with software based on our program, please cite us (this article). Thanks!

https://github.com/denispelli/CriticalSpacing/

We welcome improvements to the software. Please use GitHub to submit your suggested change.

Consent

Written informed consent for participation was obtained from each adult participant. Minors and their parents gave written consent. Children gave verbal assent and their parents gave written consent. All our human testing was conducted according to the principles expressed in the Declaration of Helsinki. Our protocols were approved by: NYU University Committee on Activities Involving

Human Subjects IRB #13-9694 and #10-7375; Anglia Ruskin University Faculty Research Ethics Panel #FST/FREP/151538; Ethics Committee of the IRCCS Fondazione, Santa Lucia Rome (Prot. CE-PROG.480). Work at the Dementia Research Centre was ethically approved by the NRES Research Committee London - Queen Square (05/Q0512/47).

Author contributions

Denis conceived the method, designed the "Pelli" font, wrote the testing software CriticalSpacing.m, and reached out to the other authors to help test it. Denis wrote the first draft, and everyone else helped polish it. Sarah, Marialuisa, Sebastian, Silvia, Keir, Marjorie, and Kathryn helped adapt the testing to accommodate children and dementia patients. Sarah, Marialuisa, Silvia, Kathryn, Keir, and Xiuyun recruited and tested observers. Hörmet designed the "$" character in the Pelli font, helped write the MATLAB testing software, and helped analyze the results. Hörmet created an unfamiliar very thin "Sticks" font that was an important step towards the "Pelli" font. Hannes designed a new font Arouet for this project, which performed better than any other font available then; our tests with Arouet led to the design of the new Pelli font, which achieves smaller legible width. Hannes converted Denis's PNG drawings into the computer-installable Pelli font. All authors have agreed to the final content.

Competing interests

No competing interests were disclosed.

Grant information

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We confirm that the funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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Christopher Tyler
Brain Imaging Center, Smith-Kettlewell Eye Research Institute, San Francisco, CA, USA

In general, this is an excellent presentation of the capabilities of a new font designed for the measurement of foveal crowding.

In relation to terminology, the standard physical and mathematical unit “arcmin” is to be preferred to the ill-formed “minarc”.

In the Introduction it should be clarified that eq 3 is derived from eqs 1 & 2.

Are the cited studies of foveal crowding compatible with a 1.7:1 ratio of crowding to acuity?

The Vernier acuity limit is closer to 0.1 arcmin than 0.01 deg, and its ratio to its crowding spacing would be much greater than 10:1. According to Levi et al. (1985), the maximal crowding is at 3 arcmin for a ~0.1 arcmin foveal Vernier acuity, or a 30:1 ratio.

Fig. 7 caption. “ratio” should be plural in “several spacing:size ratio”. The significance of the invariance of threshold with spacing:size ratio is obscure. It might be clearer to say “threshold spacing of each observer is proportional element size rather than conforming to a fixed spacing independent of element size”.

The Discussion should specify what is 6 mm in V1. Is this the diameter of the (circular) crowding zone?

In suggesting that the crowding is limited by the number of neurons/mm^2 in cortex, it should clarify that the number of neurons within a 6 mm diameter crowding zone would be roughly 1.5 million just in V1, and perhaps 5 million throughout the visual hierarchy. Is this the number that are expected to participate in the acuity performance?

The Discussion should reflect the studies of the Cavanagh on the attentional window hypothesis of crowding.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Competing Interests: No competing interests were disclosed.

Author Response 16 Feb 2016

Denis Pelli, New York University, USA

Dr. Christopher Tyler
Smith-Kettlewell Eye Research Institute

Dear Christopher,

Thank you for your timely and helpful review.

In general, this is an excellent presentation of the capabilities of a new font designed for the measurement of foveal crowding.

Thank you.

In relation to terminology, the standard physical and mathematical unit "arcmin" is to be preferred to the ill-formed "minarc".

Agreed. We'll change to: arcmin.

In the Introduction it should be clarified that eq 3 is derived from eqs 1 & 2.

Yes. We'll do that.

Are the cited studies of foveal crowding compatible with a 1.7:1 ratio of crowding to acuity?

We agree that our measure should be compared to the prior literature, but we think that it's more appropriate to forget acuity and just compare crowding directly. The crowding-to-acuity ratio is dimensionless, a ratio of degrees to degrees, but it is not fundamental. Pelli et al. (2006) Fig. 5b and Pelli et al. (2007) Fig. 6, reproduced below, showed that critical spacing (center to center) is independent of the letter size used to measure it. They got the same critical spacing despite varying letter size over a 2:1 range. Pelli and Tillman (2008) Fig. 5 provides demos, reproduced below, showing that critical spacing is independent of target size. Thus we expect the critical spacing of crowding in the healthy fovea to be a fixed constant, independent of the font and letter size used to measure it. Acuity (threshold size) depends strongly on the font, so the variable ratio is less interesting than the critical spacing itself, which should not change.

FIGURE: Critical spacing data from Pelli et al. (2007) Figure 6. Reproduced here:
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3624758/figure/F2/
The axes indicate position in the visual field, relative to the fixation point (grey "+" in upper left). In the upper right, also gray, we show a triplet: a target letter between two symmetrically arranged flankers. The colored contour lines trace out the center-to-center target-to-flanker spacing the observer required to achieve 80%-correct identification of the target letter. At each eccentricity, the black, red, and green curves represent different letter sizes. We used larger letters at more peripheral locations, but the large letter size (plotted green) was always approximately twice the small letter size (plotted red). The results show that the critical spacing is proportional to radial eccentricity and independent of letter size.

FIGURE: Critical spacing demo from Pelli and Tillman (2008) Figure 5. Reproduced here:

http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3624758/figure/F3/
Critical spacing is independent of object and size. Fixating on a red minus, you will be unable to identify the middle object in that row unless you isolate the target object by hiding the flanking objects with your fingers (or two pencils). The ± is our estimate of the fixation point where you can just barely identify the target. Note that the task is easy when you fixate to the right of the ± and hard when you fixate to the left. **In rows 1-2, 3-4, and 5-6, note that doubling object size has no effect on critical spacing.**

It is easy to measure the critical spacing of crowding in the periphery, where it has much longer range than most other effects. It is not easy to measure it in the fovea, where a measured spacing threshold may in fact be limited by acuity or overlap masking.

Song et al. (2014) found distinct relationships between threshold size and spacing for the three mechanisms. **Crowding** has a fixed threshold spacing, independent of size. **Acuity** is a fixed threshold size, independent of spacing. **Overlap masking** produces a threshold spacing proportional to threshold size, with a ratio of 1.4. We look for these signatures here, taking conservation of threshold spacing across size as evidence for crowding.

The conservation of our 0.05 deg estimate across letter size is strong evidence that it's a crowding limit. Indeed, at the 0.05 deg threshold size of the Sloan font, two letters will be touching at a 0.05 deg center-to-center spacing. Legibility will be impaired by overlap masking, which extends to a spacing of 1.4 times the acuity size (Song et al.2014). Some studies used tiny targets (e.g. Vernier) to obtain crowding estimates consistent with this (e.g. Levi et al., 1985; Malania et al., 2007). Other studies used bigger targets, like the Sloan font, which cannot measure a spacing as small as that, and end up reporting larger threshold spacings that are limited by overlap masking or acuity, not crowding. We'll add this point to the paper. Thanks!

The Vernier acuity limit is closer to 0.1 arcmin than 0.01 deg.

Oops. Yes, thanks for catching this. We'll fix it.

and its ratio to its crowding spacing would be much greater than 10:1. According to Levi et al. (1985), the maximal crowding is at 3 arcmin for a ~0.1 arcmin foveal Vernier acuity, or a 30:1 ratio.

As noted above, the ratio is not conserved by crowding. Crowding conserves the threshold spacing. 3 arcmin is 0.05 deg, which agrees with our 0.05 deg estimate made with the Pelli font.

Fig. 7 caption. "ratio" should be plural in "several spacing:size ratio".

Yes. Thanks. We'll fix it.

The significance of the invariance of threshold with spacing:size ratio is obscure. It might be clearer to say "threshold spacing of each observer is proportional element size rather than conforming to a fixed spacing independent of element size".

Uh oh. This is an important point, which we need to explain better. As noted above, conservation of threshold spacing, independent of size, is evidence of crowding (Pelli et al. 2006; Pelli et al. 2007; Song et al. 2014). Thus Fig. 3 shows that the Pelli font tests crowding, and the Sloan font does not, because the Pelli threshold spacing is conserved across size while the Sloan threshold is not.

Thank you very much for insisting that we be clear.

The Discussion should specify what is 6 mm in V1. Is this the diameter of the (circular) crowding zone?

Good point. It's radius, not diameter. 6 mm is the critical spacing, which is the radius of the crowding area, centered on the target (Pelli, 2008). At the visual field, the Bouma law tells us that threshold is linearly related to eccentricity. The logarithmic mapping of the cortical magnification factor (cortical position ∝ log eccentricity) results in a critical spacing on the surface of the cortex that is independent of eccentricity.

In suggesting that the crowding is limited by the number of neurons/mm^2 in cortex, it should clarify that the number of neurons within a 6 mm diameter crowding zone would be roughly 1.5 million just in V1, and perhaps 5 million throughout the visual hierarchy. Is this the number that are expected to participate in the acuity performance?

The critical spacing of crowding is 6 mm in V1 and 5 mm in V2 (Pelli, 2008). The density of cortical neurons is conserved, about 370,000/mm^2 in V1 and 150,000/mm^2 in the rest of cortex, across individuals and mammalian species (Rockel et al. 1980; Braitenberg & Shüz, 1998), so a circle in V1 with 6 mm radius encompasses 41,000,000 neurons. That is an upper bound on number of participating V1 neurons. For V2, the radius is 5 mm, and the neural density is lower, so the radius encompasses 12,000,000 neurons.

The Discussion should reflect the studies of the Cavanagh on the attentional window hypothesis of crowding.

Yes, will do. Freeman & Pelli (2007) present a long discussion of He et al. (1996) and Intriligator & Cavanagh (2001).

Thank you.

Denis Pelli & Sarah Waugh on behalf of the authors,

Denis & Sarah

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Competing Interests: No competing interests were disclosed.

Referee Report 22 January 2016

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Arnold Wilkins
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Visual crowding is a poorly understood phenomenon, the neural origins of which are “hotly debated”[1]. It can occur at various levels in a perceptual hierarchy, including that of objects [1]. Information is not necessarily lost but can become misappropriated, and, perhaps in consequence, critical spacing differs across stimulus categories [2]. It is exaggerated in clinical cases to the extent that objects sometimes cannot be discerned unless presented singly in an uncluttered scene [3].

The authors of this paper clearly take the view that crowding is one thing rather than several. It may or may not be one thing, but this does not matter here. Pelli and co-authors present some very challenging ideas and data, together with techniques that have exciting potential in the clinic.

The following are simply thoughts that have occurred to me on reading the report. They are not suggestions for alterations to the draft, with the exception of the list of items at the end.

I have some reservations as to the use of highly contrasted spatially periodic material. We showed that single words and words in sentences are read by fluent readers about 10% more slowly when they have a high first peak in the horizontal autocorrelation of the image of the word. When the component strokes of

the letters have a spatial periodicity, as in the word mum, the words are slower to read[4]. Jainta, Jaschinski and I showed that some of this slowing was due to the time taken for the eyes to re-establish vergence with minimum error following a saccade[5].

Similar considerations may apply to the use of periodic strokes in the Pelli font when the font is observed with both eyes. Some of the difficulty in reading the letters may be due to vergence correction. If so, monocular viewing may reduce the effects of the spatial periodicity relative to binocular viewing. One might expect the usual reduction in acuity with monocular viewing, but on this account the reduction might be less for the Pelli font because it compromises vergence?

A second and related consideration concerns pattern glare. This term refers to the perceptual distortions and instability experienced by some observers on viewing spatially periodic arrays, in particular gratings with spatial frequency within one octave of 3 cycles/degree[6]. Such arrays would include those of similar letters presented across the page, as a result of both the letter strokes and the lines of letters, depending on scale. Perceptual distortions are usually accompanied by discomfort. Did observers report perceptual distortions, particularly instability (apparent movement) of the letters when presented in closely spaced arrays? If so, did they then have a higher threshold and report discomfort?

If the Pelli font is to be used with children it would be nice to have data showing how readily (e.g. with what speed) they can name the digits 1-9 when presented in isolation, and how this changes with age. I suspect that digits in which a contour is represented as a filled square might be particularly difficult for young children to recognise. These digits include 4, 6, 8 and 9. Is it necessary to include these digits? Without them, the choice is 1 of 5, which is surely sufficient to be used in rapid clinical assessment. After all, most alphabetic charts use only a subset of the letters of the alphabet and this difference between the perceived set size and actual set size does not appear to present the problems that might be anticipated.

As regards the particulars of the report:

1. There is an infelicity somewhere in the sentence that currently reads: “That needed spacing grows linearly with eccentricity”.

2. Please could the unpublished report by Strappini *et al* be made available for download?

3. Please could we have some numbers to support the statement that “We’ve had good results from this with the several children we have tested so far.”

4. Please could we have a citation or two to support the assertion that “Similarly, crowding has been linked to reading speed in children and in patients, so…”

5. The statement that “As in Regan’s chart, no matter where the observer’s eye lands on the screen, a target will be imaged on the observer’s fovea” seems a little optimistic without a word or two of additional explanation.

All in all, this is a fascinating piece of original research, and I hope the promise of clinical use is borne out. I, for one, would like to know whether there is a relationship between pattern glare and crowding. If there is, it might be possible to bring together two disparate aspects of the literature, which would have useful theoretical spin-off.

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I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Competing Interests: No competing interests were disclosed.

Author Response 16 Feb 2016

Denis Pelli, New York University, USA

Professor A J Wilkins
Department of Psychology
University of Essex

Dear Arnold,

Thanks very much for your quick and thoughtful review.

We appreciate your work on how periodic structure impairs acuity and reading (Wilkins et al. 1989; Wilkins et al. 2007; Jainta et al., 2010). Yes, reducing periodicity might allow a reduction of the size or spacing limit. It's interesting that one of the most revered experts on type design, Gerrit Noordzij (1985/2005), professor of typeface design at the Royal Academy of Fine Arts in The Hague, Netherlands, wrote that the best type has an even alternation of white and black, which seems to advocate optimizing font design by maximizing the same periodicity that your research recommends minimizing.

We don’t yet have any reports of discomfort (Wilkins et al. 1984). We'll record such reports to correlate with results. Thanks.

Our paper includes testing on two 8-year olds. Their time per trial and critical spacing were similar to those of the adults we tested. We will be collecting a lot more data on children, down to age 4. We'll keep track of which letters they have trouble with (time and accuracy), and, if necessary, we will adjust or drop (as you suggest) troublesome letters.

We share your interest in individual differences in reading (Bouldoukian et al., 2002). In our study, Drs. Martelli (U. Rome Sapienza & IRCCS Fondazione Santa Lucia), Waugh (Anglia Ruskin U.), and Rhodes (NYU) are testing school-age children, including many with dyslexia or amblyopia.

Regarding your numbered points:

1. There is an infelicity somewhere in the sentence that currently reads: “That needed spacing grows linearly with eccentricity”.

Yes, this would be better: "This critical spacing grows linearly with eccentricity”

2. Please could the unpublished report by Strappini *et al* be made available for download?

We can't. It’s under review at another journal. *F1000Research* journal style designates this as an "unpublished report". We have sent you a copy privately.

3. Please could we have some numbers to support the statement that “We’ve had good results from this with the several children we have tested so far.”

As noted above, we reported our results on two 8 year olds. We will be testing children in Cambridge (Waugh), New York (Rhodes), and Rome (Martelli).

4. Please could we have a citation or two to support the assertion that “Similarly, crowding has been linked to reading speed in children and in patients, so…”

See Fig. 9 and associated discussion in
Pelli, D. G., & Tillman, K. A. (2008) The uncrowded window of object recognition. *Nature Neuroscience*, 11(10):1129 - 1135. doi: 10.1038/nn.2187
http://www.nature.com/neuro/journal/v11/n10/index.html#pe
They cite:
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5. The statement that “As in Regan’s chart, no matter where the observer’s eye lands on the screen, a target will be imaged on the observer’s fovea” seems a little optimistic without a word or two of additional explanation.

This may help: “Because the screen is covered with letters less than 1 degree apart, no matter where the eye lands, at least one letter will be imaged in the observer’s 1 deg foveola.”
Thank you.
Denis, on behalf of my coauthors.

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