METHOD ARTICLE

A clinical test for visual crowding

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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 eccentricity in the periphery. Foveal crowding is much worse in certain patient groups, including 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 in the fovea. 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.

Keywords

Crowding, critical spacing, repeated letters, neural density

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; Pelli & Tillman, 2008; Levi, 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, Levi, & Pelli 2014; Strappini, Pelli, Di Pace, & Martelli, under review). There is some evidence that the critical spacing of crowding drops during childhood as reading speed increases (Kwon, Legge, & Dubbels, 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 and Legein, 1977; O'Brien, Mansfield, and Legge, 2005; Martelli, Di Filippo, Spinelli, and Zoccolotti, 2009)

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, Levi, & Pelli, 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, et al., under review). 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, Klein, & Aitsebaomo, 1985; Toet & Levi, 1992). Based on their measurements in the peripheral visual field, Song et al. (2014) provided these formulas:

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

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

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 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

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

$$= 10.3\ (\varphi + 0.45\ \text{deg})\ /\ (\varphi + 2.72\ \text{deg}), \tag{3}$$

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 acuity 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, Pimm-Smith, Evans, Harding, & Braddick, 1986; Danilova & Bondarko, 2007;

Semenov, Chernova, & Bondarko, 2000; Hess, Dakin, & Kapoor, 2000; Siderov, Waugh, & Bedell, 2013; Bedell et al. 2013; Bedell et al. 2015; Malania, Herzog, & Westheimer, 2007; Liu & Arditi, 2000; Kwon, Legge, & Dubbels, 2007). 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 a good 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 and Robson, 1991). Vernier targets (two lines that may be just barely out of alignment) are very thin, and discriminable, but offer only two categories. To get many categories, we needed recognizable objects. We needed a font that can be identified at a tiny width, a small fraction of the 0.05 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 Fig. 1.

		Height:width	Width:stroke
Pelli	1 2 3 4 5 6 7 8 9	5:1	2:1
Sloan	D H K N O R S V Z	1:1	5:1

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). (Both are available; see Software availability.)

Figure 2 allows you to test your own eye. The figure is an acuity test chart, but this test in 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 height, 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., 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.

Figure 2. An acuity chart for width, for three fonts: Pelli, Gotham Condensed Light, and Sloan. On each line there are three fonts, and all characters on the line have the same width, though their heights vary greatly. Each line down is smaller, by a factor of $2^{-0.5}$ = 71%. Thus, going down two lines halves the letter size. Sloan is the USA standard for acuity testing. It has a 1:1 aspect ratio. Of all the commercially available fonts that we tested, Gotham Condensed Light, with 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 0.10 deg for Sloan. You can use this chart to confirm this for your own eyes. At any viewing distance, once you reach your limit for Sloan, you’ll be able to read two more line of Gotham and four more lines of the Pelli font. Copyright 2016, Denis G. Pelli.

SPECIAL POPULATIONS

To test children as young as 4 years, we considered the use of the popular drawings, such as Lea Symbols and Patti Pics, used for illiterate testing, but they seemed unlikely to yield the tiny threshold width we need (Mercer, Drover, Penney, Courage, & Adams, 2013). Thus, we decided to use numbers, anticipating that most children will have some familiarity. We give 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 chart 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.

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. This ratio provides enough space to avoid overlap masking (Song, Levi, & Pelli, 2014). Song et al. distinguish three phenomena that affect legibility of fine text: acuity, crowding, and overlap masking. Overlap masking is avoided by using a spacing:size ratio of at least 1.4. Once overlap masking has been thus excluded, they report no interaction between the size limit of acuity and the spacing limit of crowding; a target letter is identifiable if and only if the target and flankers satisfy both limits.

The observer is asked to identify both targets in each presentation, in any order, and each identification 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 observers, 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, Palomares, & Majaj (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

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 266 pixel/deg, so that a 0.03 deg letter will be at least 8 pixels wide. The minimum distance depends on the screen resolution of the particular laptop.

Our experiments ran in MATLAB with the Psychtoolbox extensions on laptop computers running OS X or Windows (Kleiner, Brainard, Pelli, 2007).

We use a wireless keyboard 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 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 computers says “Congratulations” at the end of the run.

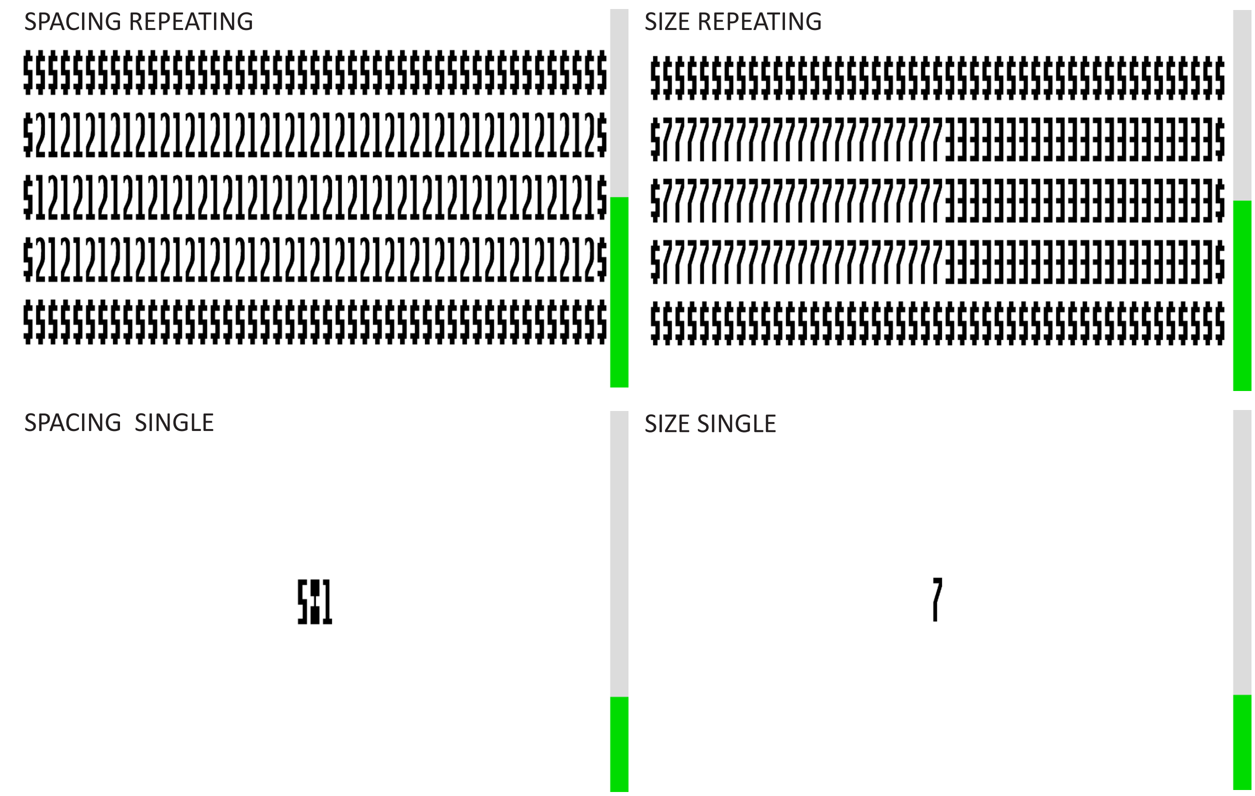

Figure 3. Four screenshots taken during testing, one for each kind of threshold measurement. The green bar at the right of each screenshot indicates progress through the run of 20 trials (ten presentations of repeating targets or 20 presentations of single targets). Threshold for spacing with repeating targets (left upper) and a single target (left below). Threshold for size with repeating targets (right upper) and with a single target (right below).

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

SPACING-REPEATING	New! Two alternating targets repeated over the whole screen (Fig. 2A).
SPACING-SINGLE	Traditional. A single target between two flankers.
SIZE-REPEATING	The screen is divided into two halves, left and right. Each half shows a single target, repeated to fill the space.
SIZE-SINGLE	Traditional. A single target.

In the REPEATING conditions there are two different targets; in the SINGLE 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 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 REPEATING 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, “$” or “X” around the edge on every REPEATING presentation. The outer edge of the display on REPEATING trials is always a non-informative “margin” character that is not part of the target alphabet. When the alphabet is “DHKNORSVZ”, we use “X” on the margin. When the alphabet is “123456789”, we using “$” 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 two random flankers (drawn randomly from the alphabet), left and right.

In the REPEATING 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, Pelli, and Levi (2014). One parameter (horizontal size or spacing) is controlled by QUEST. The other parameter scales proportionally in a fixed ratio of spacing to size, which is usually 1.4:1, but we also tested 1.2, 1.5, and 1.8. 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 repeating 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.

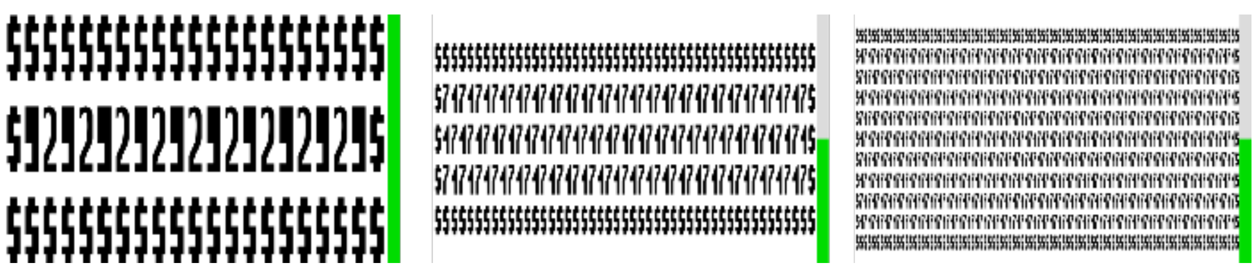

Figure 4. Screenshots at three different spacings in the SPACING REPEATING condition.

Results

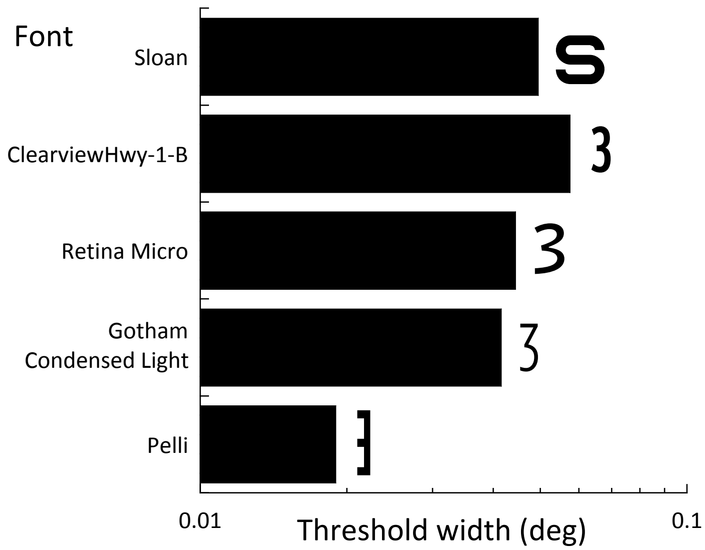

Figure 5. Threshold width of various fonts.

We measured threshold width for various fonts that have a reputation for legibility at small angular subtense. ClearviewHwy 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 Pelli escapes to achieve a much smaller threshold size, of 0.02 deg for this observer, XW.

We measured threshold spacing with repeating targets with the Pelli font on 6 observers (four adults, 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. Threshold spacing mean±se was 0.065±0.006 (repeating) and 0.049±0.004 (single).

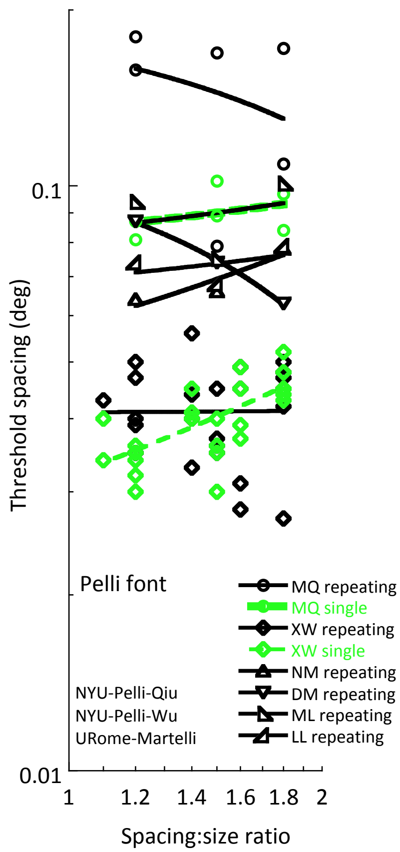

Figure 6. The critical spacing of crowding. Spacing thresholds measured with the Pelli font. Critical spacing is 0.05 (single) or 0.065 (repeating). The different critical spacings of the observers are conserved across this range of spacing to size ratio. The line slopes are practically zero, consistent with spacing-limited threshold and inconsistent with the unit slope of a size limit. Observers NM and DM are 8 year old children; the rest are adults.

This small difference (0.065 vs 0.049 deg) is significant, about three standard errors. However, two observers did both conditions and only one showed a difference. The slightly stronger crowding in the repeating condition could be because the repeating target was flanked on all four sides by other digits, whereas the single target was flanked only on left and right.

Overlap masking is negligible at the large ratios of size to spacing that we used (Song, et al. 2014). So a single threshold measured by co-varying size and spacing might be hitting either a size or spacing limit. The hypothesis that the thresholds are spacing-limited predicts that the measured spacing threshold will be independent of the spacing:size ratio. The hypothesis that the thresholds are size-limited predicts that the measured 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. We did linear regressions to estimate the log-log slope of all the data for each of the 8 observers. Across all the observers, the log-log slope mean±se is 0.018±0.169, which is insignificantly different from zero and nearly 5 standard errors below 1. This confirms that these spacing thresholds are spacing-limited, not size-limited.

Discussion

NEURAL DENSITY AND CROWDING

Strappini, Pelli, Di Pace, and Martelli (under review) 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. They further note that peripheral vision, strabismic amblyopia, and apperceptive agnosia are all limited by crowding, making it urgent to know what drives crowding. Acuity does not. Song, Levi, & Pelli (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 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, one etiology for apperceptive agnosia (Crutch, 2014). Crutch and Warrington (2007, 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. From this perspective, crowding in central vision of the agnosic patients may reflect limited plasticity of the ventral stream, i.e. insufficient recruitment of other neurons to entirely make up for the loss.

We will be using this new test to measure crowding in children and adults, healthy and patients, to develop norms and address questions of whether critical spacing might track neural density.

Conclusion

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

Data and software availability

We are providing all our threshold data as CSV spreadsheets. 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, Robson, & Wilkins, 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, Whitaker, & Bonette (1990) recommend that most studies omit the C, as we did here.

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 our institutions: NYU, Anglia Ruskin University, IRCCS Fondazione Santa Lucia of Rome Italy, Dementia Research Centre, Institute of Neurology, University College London.

Author contributions

Denis conceived the method, designed the “Pelli” font, wrote the testing software, 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.

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Figures and tables

Fig1.pdf

Figure 1. Two fonts for vision testing. The "Pelli" font is new, and 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). (Both are available; see Software availability.)

Fig2.pdf

Figure 2. An acuity chart for width, for three fonts: Pelli, Gotham Condensed Light, and Sloan. On each line, there are three fonts, and all characters on the line have the same width, though their heights vary greatly. Each line down is smaller, by a factor of $2^{-0.5}$ = 71%. Thus, going down two lines halves the letter size. Sloan is the USA standard for acuity testing. It has a 1:1 aspect ratio. Of all the commercially available fonts that we tested, Gotham Condensed Light, with aspect ratio 2.8:1, has the narrowest legible width. We created several experimental fonts (Arouet and Sticks, not shown) and final created the “Pelli” Eye Chart 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 0.10 deg for Sloan. You can use this chart to confirm this for your own eyes. At any viewing distance, once you reach your limit for Sloan, you’ll be able to read two more line of Gotham and four more lines of the Pelli font. Copyright 2016, Denis G. Pelli.

Fig3.pdf

Figure 3. 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 repeating targets or 20 presentations of single targets). Threshold for spacing with repeating targets (left upper) and a single target (left below). Threshold for size with repeating targets (right upper) and with a single target (right below).

Fig4.pdf

Figure 4. Screenshots at three different spacings in the SPACING REPEATING condition.

Fig5.pdf

Figure 5. Threshold width of various fonts.

Fig6.pdf

Figure 6. The critical spacing of crowding. Spacing thresholds measured with the Pelli font. Critical spacing is 0.05 (single) or 0.065 (repeating). The different critical spacings of the observers are conserved across this range of spacing to size ratio. The line slopes are practically zero, consistent with spacing-limited threshold and inconsistent with the unit slope of a size limit.