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Is 20/20 vision good enough? Visual acuity differences within the normal range predict contour element detection and integration

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Abstract

Contour integration (CI) combines appropriately aligned and oriented elements into continuous boundaries. Collinear facilitation (CF) occurs when a low-contrast oriented element becomes more visible when flanked by collinear high-contrast elements. Both processes rely at least partly on long-range horizontal connections in early visual cortex, and thus both have been extensively studied to understand visual cortical functioning in aging, development, and clinical disorders. Here, we ask: Can acuity differences within the normal range predict CI or CF? To consider this question, we measured binocular visual acuity and compared subjects with 20/20 vision to those with better-than-20/20 vision (SharpPerceivers) on two tasks. In the CI task, subjects located an integrated shape embedded in varying amounts of noise; in the CF task, subjects detected a low-contrast element flanked by collinear or orthogonal high-contrast elements. In each case, displays were scaled in size to modulate element visibility and spatial frequency (4-12 cycles/deg). SharpPerceivers could integrate contours under noisier conditions than the 20/20 group ($p=.0002$) especially for high spatial frequency displays. Moreover, although the two groups exhibited similar collinear facilitation, SharpPerceivers could detect the central target with lower contrast at high spatial frequencies ($p<.05$). These results suggest that small acuity differences within the normal range—corresponding to about a one line difference on a vision chart—strongly predict element detection and integration. Furthermore, simply ensuring that subjects have normal or corrected-to-normal vision is not sufficient when comparing groups on contour tasks; visual acuity confounds also need to be ruled out.

Contour integration (CI) rapidly represents co-oriented and spatially aligned elements (e.g., “Gabor”) as belonging to a single continuous contour (Field, Hayes, & Hess, 1993). Collinear facilitation (CF) is a related visual process in which a low-contrast Gabor becomes easier to see when flanked by appropriately spaced high-contrast Gabors collinear to the target (Polat & Sagi, 1993). Studies in psychophysics, electrophysiology, fMRI, and single unit recording have shown that CI and CF are mediated partly via long-range excitatory horizontal connections between orientation-tuned spatial frequency filters in V1/V2 (Hess, Hayes, & Field, 2003). Given that the neurobiological substrate of CI and CF is well explored, tasks probing the processes have proven useful in evaluating visual cortical functioning in the context of aging (Chan, Battista, & McKendrick, 2012; Roudaia, Bennett, & Sekuler, 2008), autism (Del Viva, Igliozi, Tancredi, & Brizzolara, 2006; Keita, Mottron, Dawson, & Bertone, 2011), development (Kovacs, Kozma, Feher, & Benedek, 1999), schizophrenia (Keri, Kelemen, Benedek, & Janka, 2005; Silverstein, Kovacs, Corry, & Valone, 2000), dyslexia (Simmers & Bex, 2001), drug abuse (White, Brown, & Edwards, 2013), and amblyopia (Chandna, Pennefather, Kovacs, & Norcia, 2001; Polat, Sagi, & Norcia, 1997), among other cases. In most of these studies, subjects have “normal or corrected-to-normal” vision, which—on its strictest definition— corresponds to a 20/20 cut-off. But the average visual acuity (VA) of healthy adult eyes in humans is significantly *better* than 20/20 (Elliott, Yang, & Whitaker, 1995). Therefore, we ask: Do VA differences within the normal range modulate contour grouping performance? It is possible that slight reductions in VA might impair the detection of orientation, spatial frequency, position, or contrast, which in turn might weaken integration processes that rely on these features. Such a finding would present an important confound in contour studies whenever a population plausibly differs in VA, potentially blocking inferences about contour integration circuitry (lateral interactions). Such a finding would also offer a novel explanation of individual differences in contour grouping tasks and demonstrate that seemingly irrelevant differences in visual acuity within the normal range can predict contour grouping behavior. (*Footnote:* VA decrements could also conceivably lead to enhanced integration, perhaps because of heightened reliance on an advantageous low SF filter. This scenario would also be informative for identifying confounds and understanding individual differences on perception tasks).

To examine this issue, we compared subjects with 20/20 vision to those with better-than-20/20 vision (hereafter, SharpPerceivers) on two contour grouping tasks. In the CI task, a closed circular chain of Gabor elements appeared among a varying number of randomly oriented noise elements and subjects identified the quadrant thought to contain the circular target (Ciaramelli, Leo, Del Viva, Burr, & Ladavas, 2007). In the CF task, a central low contrast Gabor target was presented between collinear or orthogonal high-contrast flankers and subjects determined on each trial whether the target was present or absent. In both tasks, the size of the display was scaled so that Gabors were drawn with a lower spatial frequency (4 cycles/deg) or a higher spatial frequency (10 or 12 cycles/deg). Scaling in this way allowed us to examine whether visual acuity differences become more relevant for less discernible Gabor features.

Methods

Subjects

Twenty psychophysically naïve adults (mean age=41.4; 10 female) with normal or corrected-to-normal VA performed a CI task (Ciaramelli et al., 2007). Subject data derived from the now-completed first phase of a larger clinical study on vision. VA was established binocularly with a logarithmic Sloan visual acuity chart (PrecisionVision, LaSalle, Illinois) presented under fluorescent overhead lighting. Visual acuity values were expressed as logMAR units (the logarithm of the minimum angle of resolution, or the $\log_{10}$ of the Snellen fraction inverse). The lower testing limit of the chart was 20/10 (logMAR=-0.3). Visual acuity estimates were obtained with the chart-recommended viewing distance of 2 meters; such estimates are robust and apply to a variety of distances, including those employed in our study (.88 meters and 1.82 meters) (Heron, Furby, Walker, Lane, & Judge, 1995, p. 25). One group of subjects had 20/20 vision (logMAR=0; hereafter the 20/20 group; N=10); the other group had 20/16 or 20/12.5 vision (N=8 and N=2, respectively; hereafter, the SharpPerceivers). The 20/20 group and SharpPerceivers did not differ on age ($M=42.3$ and 40.5 , respectively; $p=.76$) or sex (4 and 6 females, respectively, $p=.66$) and no participant reported psychiatric or visual pathology. The research followed the tenets of the Declaration of Helsinki; subjects provided informed written consent upon being apprised of the nature and possible consequences of the study; and the research was approved by the Rutgers IRB.

Apparatus

Subjects viewed stimuli from a chinrest on a 21" CRT monitor in a darkened room. The screen had a resolution of 1024×768, a frame rate of 100 HZ noninterlaced, and a mean background luminance of 30 cd/m². Lookup table values for the monitor were linearized with psychophysics toolbox (Brainard, 1997) and calibrated with a Konica-Minolta CS-100 photometer.

Stimuli & Procedure: Contour integration—The contour integration experiment comprised a lower spatial frequency (LSF) and a high spatial frequency block (HSF) of trials, which were counterbalanced across observers. Stimuli consisted of Gabor patches, which are oriented sinusoids multiplied by a circular Gaussian:

$$G(x, y, \theta) = c \sin(2\pi f(x \sin \theta + y \cos \theta)) \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right)$$

where (x, y) denotes the distance in degrees from the center of the element, θ is the element's orientation (in deg), f is the peak spatial frequency of the element, and c is Michelson contrast. In the LSF block, Gabors had a sine phase (to create a balanced luminance profile), 95% contrast, a peak spatial frequency of 4 cycles/deg, and a Gaussian envelope SD (space constant) of 7.3 arcmin. The stimulus area (target + noise) subtended 19.9 deg on a side. The circular target (diameter= 7.37 deg) consisted of twelve equally spaced Gabors (spacing=1.93 deg) and was positioned at a quadrant center with randomly added jitter (± 0.5 deg along each dimension). The target quadrant was randomly assigned on each trial and

never contained a unique number of Gabors relative to neighboring quadrants. Noise Gabors never overlapped with each other or the target Gabors, and ranged in number from 36 to 464 depending on the staircase recommendation (see below). Stimuli in the high spatial frequency block (HSF) were the same as the LSF block, except that the entire stimulus was scaled to one-third the retinal size (e.g., so that Gabors had a peak SF of 12 c/d). Scaling was achieved by shrinking the stimulus display and increasing the viewing distance from 87.6 cm to 181.5 cm. Modulating spatial frequency via viewing distance imposes little effect on contour integration from 3 to 24 cycles/deg (Hess & Dakin, 1997).

On each trial, an array of oriented Gabors appeared for 1000 milliseconds after which subjects saw a homogeneous gray screen with numbers 1 through 4 centered in each quadrant (see Figure 1A). Subjects were given an unlimited amount of time to identify the target quadrant number and did not receive feedback on response accuracy.

Within a block, there were three randomly interleaved Bayesian adaptive staircases—30 trials per staircase—and each determined the number of noise patches needed to yield 75% accuracy (Watson & Pelli, 1983). The three threshold estimates were averaged to produce one value per SF per subject. Fifteen catch trials (without noise) also appeared randomly in each block to ensure that all subjects were on task. Prior to the CI experiment, subjects received 20 practice trials that were of the same SF as the subsequent non-practice trials.

Stimuli & Procedure: Collinear Facilitation—Stimuli in this experiment were viewed from a distance of 181.5 cm. One half of the collinear facilitation experiment consisted of LSF stimuli and the other half consisted of HSF stimuli and the two block types were counterbalanced across observers. In the LSF trials, there were three vertically aligned Gabor elements centered on a mean gray background (45 cd/m²). The Gabors were drawn with the same formula as above; each had a sine phase, a peak spatial frequency of 4 cycles/deg, and a Gaussian envelope SD of 10.6 arcmin. The central Gabor was vertically oriented and separated from the flankers by 4 lambda (wavelength) center-to-center. Stimuli in the high spatial frequency (HSF) trials were similar to the LSF trials, except that the entire stimulus was scaled to 40% the retinal size (e.g., Gabors had a peak SF of 10 c/d). Similar to an earlier study (Polat, 2009), we increased the flanker contrast from 64% in the LSF block to 94% in the HSF block so that the latter would be easier to see. Flanker contrast differences within this range do not alter facilitation for lower SF stimuli (Polat, 2009).

Each trial began with a white fixation cross centered on a gray background. Immediately after initiating a trial, the observer saw a blank screen (400 ms), a three Gabor array (90 ms), and then another gray screen until a response was provided (present or absent). We opted to present the stimulus on every trial rather than use a two-interval forced choice since qualitatively the same results arise in the two cases (Keri et al., 2005) and since the former allows for a shorter experiment. A 1-up, 3-down staircase determined the threshold, the amount of contrast needed to see the stimulus 79.4% of the time (Wetherill & Levitt, 1965). Specifically, in the event of one incorrect response (miss), the contrast between the background and the central Gabor increased by 0.1 log units (26%) and in the event of three consecutive correct responses (hit), the contrast decreased by the same amount. A decrease or increase of contrast preceded by a contrast change in the opposite direction was labeled a

‘reversal’, and a block of trials terminated after seven reversals. Threshold for a condition was computed as the average contrast (in log units) for all the trials following the 4th reversal. (Averaging contrasts over all trials rather than just the reversal values improves threshold estimates (Klein, 2001, p. 1449)).

In each half of the experiment, there were two blocks corresponding to whether the flankers were orthogonal or collinear to the central target. The two blocks were counterbalanced across observers and so too was the SF ordering. Collinear facilitation was measured as the threshold in the orthogonal minus the collinear conditions, with larger (positive) differences reflecting more facilitation. Subjects began each half of the experiment with 25 practice trials without flankers.

Analysis

For the CI task, groups were compared with two 2 (SF) by 2 (group) mixed model analyses of variance (ANOVA)—once for the catch trials (percent correct) and once for the non-catch trials (threshold averages). For the CF task, groups were compared with a 2 (SF) by 2 (facilitation) $\times$ 2 (group) mixed-model ANOVA.

Results

In the CI task, catch trial performance exceeded 98.5% accuracy for each group and SF condition, indicating that all subjects easily saw the target without noise (all $ps > .35$). More interestingly, as shown in Figure 1, the 20/20 group had lower thresholds (worse performance) than the SharpPerceivers ($F(1,18)=21.5$, $p=.0002$, $\eta_p^2=.545$; See Supplementary Material for scatterplot). The group difference depended on SF ($F(1,18)=6.40$, $p=.021$, $\eta_p^2=.262$): whereas the SharpPerceivers performed the same regardless of SF ($t(8)=-1.27$, $p=.236$), consistent with prior studies (Hess & Dakin, 1997), the 20/20 group performed worse in the HSF block, probably because of reduced Gabor visibility ($t(9)=2.36$, $p=.042$). Despite the interaction, follow-up comparisons revealed higher thresholds for the SharpPerceivers at each SF (LSF, $t(18)=3.10$, $p=.006$; HSF, $t(18)=4.19$, $p=.0006$).

Next, we considered the results from the collinear facilitation experiment (Figure 2). There was an expected main effect of SF such that targets were less detectable (contrast thresholds were higher) for the scaled-down stimulus than for the larger display ($F(1,18)=180.2$, $p<.001$, $\eta_p^2=.909$). Contrast thresholds were also lower for collinear than orthogonal flankers ($F(1,18)=5.56$, $p=.03$, $\eta_p^2=.236$), exemplifying the classic collinear facilitation effect. In agreement with prior studies, an increase in SF lead to stronger facilitation ($F(1,18)=9.77$, $p=.006$, $\eta_p^2=.352$), possibly because signal propagation between connected neurons is faster—and more efficient—over shorter retinal distances (Polat, 2009). This interaction itself depended marginally on group ($F(1,18)=4.30$, $p=.053$, $\eta_p^2=.193$): increasing SF from 4 to 10 cycles/deg strengthened collinear facilitation more for the SharpPerceivers than for the 20/20 group. It seems that augmenting visual acuity improves sensitivity to changes in element features.

There was also a significant group by SF interaction ($F(1,18)=5.04, p=.038, \eta_p^2=.219$). Follow-up t-tests revealed that the SharpPerceivers had overall lower contrast thresholds than the 20/20 group at the high SF ($F(1,18)=4.57, p=.047, \eta_p^2=.202$) but not at the lower SF ($F(1,18)=.59, p=.452, \eta_p^2=.032$) (See Supplemental Material for scatterplot). This interaction dovetails with the contour integration results above and indicates that smaller Gabors with finer-grained features are especially hard for the 20/20 group to detect. More importantly, the collinear facilitation effect was independent of VA ($F(1,18)<0.1, p=.951, \eta_p^2<.001$).

To consider whether Gabor visibility was directly related to contour integration performance, we correlated contrast thresholds (averaged over orthogonal and collinear) with noise thresholds. It was found that—for the high SFs—subjects who needed higher target contrast could not tolerate as much noise on contour integration ($\rho=-.687, p=.0008$); for the low SF, thresholds of the two tasks did not correlate ($\rho=-.313, p=.179$).

Discussion

We considered whether VA differences within the normal range predict contour integration or collinear facilitation behavior. Slight decrements in VA might impair the detection of orientation, spatial frequency, position, or contrast, which in turn might weaken integration processes that rely on these features. It was found that—despite performing normally on catch trials—people with 20/20 vision could not tolerate as much noise when integrating contours as compared to those with superior VA, especially for high spatial frequency stimuli. At the same time, persons with 20/20 vision evinced relatively normal collinear facilitation, though their contrast detection thresholds were elevated for high SF stimuli.

Our results present a potential confound for CI studies investigating the effects of aging, development, or clinical disorders on long-range connectivity in visual cortex. Such studies draw specific inferences about visual cortical functioning without also reporting whether groups are matched on VA within the normal range. This is problematic because acuity changes across the lifespan (Elliott et al., 1995) and is potentially abnormal in a number of clinical disorders including, autism (Brosnan, Gwilliam, & Walker, 2012; Milne, Griffiths, Buckley, & Scope, 2009, p. 969) and schizophrenia (Punukollu, 2006; Viertio et al., 2007), making it unclear whether differences in VA or integration per se best explain CI performance. As an example, it is entirely possible that ocular changes (cornea, lens, pupil size) rather than dysfunctional long-range lateral connections in V1/V2 explain why persons of advanced age perform worse on contour integration. In the autism literature, VA has been found to be augmented in some studies and impaired in others (Brosnan et al., 2012; Milne et al., 2009); either result would make it hard to interpret normal contour integration performance (Del Viva et al., 2006).

We cannot rule out the possibility that prior studies matched on visual acuity without reporting it. But we consider it unlikely since there has been no reason until now to suppose that VA *should* be relevant when all subjects have at least 20/20 vision. Moreover, even if earlier studies matched on VA without reporting it, the matching would only be convincing if an appropriate eye chart was utilized, which is not always the case (see below).

We surmise that VA confounds arise not just for contour grouping tasks but also for those where subjects must inspect finely-detailed or low-visibility elements (Scialfa, Cordazzo, Bubric, & Lyon, 2013). For example, contrast sensitivity, crowding, and orientation discrimination tasks should all be reconsidered if one of the subject groups derives from a population known to have abnormal acuity. VA influences are especially worth reconsidering if researchers adopt the more liberal definition of “normal vision” established by the ICD-9-CM (Colenbrander, 2003), which places the upper bound at 20/25 (logMAR=.1). Unfortunately, many studies do not explicitly define what normal vision is, a practice that clearly impedes progress in this area.

There are ways to avoid VA confounds. First, negative logMAR values should be carefully measured and eye charts that prevent such measurement should be avoided. This recommendation may seem obvious at first, but a surprising number of charts have lower limits at 20/16 or even 20/20 (e.g., Rosenbaum Pocket Eye Chart), making it difficult or impossible to discern whether groups are actually matched on VA. Second, larger, lower SF Gabor stimuli should be employed whenever group differences in VA are expected and whenever SF composition is not critical to a study’s hypotheses. Third, groups should be either equated on VA, or at least the relationship between performance and acuity should be reported, whenever acuity is linked to the process or disorder in question. On this last point, we wish to emphasize that just as CI or CF differences are not necessarily best explained in terms of the cortex so too are VA differences not always best explained in terms of the eye. Some have argued that changes in VA parallel or perhaps are even caused by generalized cognitive changes during aging (Salthouse, Hancock, Mein, & Hambrick, 1996). In schizophrenia, deficits in acuity may reflect neurological vulnerability and portend a greater chance of converting to the illness (Schubert, Henriksson, & McNeil, 2005). Consequently, identifying a VA confound, by itself, does not preclude a cortical explanation to abnormal CI, but it would warrant a more careful investigation that teases out ocular contributions.

On a related note, we are not in a position to definitively say why our groups differed on VA and thus why the SharpPerceivers performed better. It could owe to differences in the eye’s optical system (e.g., residual refractive error) or to processing at or beyond the retina (inadequate sampling). There may be a not-yet-documented third factor—larger V1 receptive fields or more densely interconnected V1 neurons—that gives rise to better visual acuity and better element detection and integration. Although this topic will need to be further explored, we believe that residual refractive error in the 20/20 group is the most likely cause of the psychophysical differences. This is because i) normal VA is actually better than 20/20 (Elliott et al., 1995); ii) residual refractive error is extremely common among those with eyeglasses and without (Pointer, 2008); and iii) there is not yet reason to posit a third common causal factor, at least not in healthy adults.

Our data also speak to the proper usage of catch trials in contour integration studies. Both groups in our task performed almost perfectly on the catch trials even though the 20/20 group was much worse at integrating in noise. This shows that while catch trials may help assess whether subjects are understanding the instructions and adequately engaging in (i.e., attending to) the CI task, they do not provide strong evidence that all subjects are actually seeing the Gabor elements with equivalent clarity.

More generally, the foregoing results offer a new and surprisingly powerful explanation for individual differences on contour integration tasks. A one-line difference on an eye chart (0.12 logMAR units) within the normal range strongly predicts the ability to detect and integrate Gabor elements especially at higher spatial frequencies. Future studies will need to examine whether better-than-20/20 vision confers other sorts of psychophysical benefits or whether these benefits translate to more ecological contexts such as driving or navigating within low-visibility environments.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

- Brainard DH. The Psychophysics Toolbox. *Spat Vis.* 1997; 10(4):433–436. [PubMed: 9176952]
- Brosnan MJ, Gwilliam LR, Walker I. Brief report: the relationship between visual acuity, the embedded figures test and systemizing in autism spectrum disorders. *Journal of autism and developmental disorders.* 2012; 42(11):2491–2497. [PubMed: 22450702]
- Chan YM, Battista J, McKendrick AM. Aging effects on collinear facilitation. *J Vis.* 2012; 12(6):21. [PubMed: 22707428]
- Chandna A, Pennefather PM, Kovacs I, Norcia AM. Contour integration deficits in anisometric amblyopia. *Invest Ophthalmol Vis Sci.* 2001; 42(3):875–878. [PubMed: 11222553]
- Ciamarelli E, Leo F, Del Viva MM, Burr DC, Ladavas E. The contribution of prefrontal cortex to global perception. *Exp Brain Res.* 2007; 181(3):427–434. [PubMed: 17401551]
- Colenbrander A. Aspects of vision loss -- visual functions and functional vision. *Visual impairment research.* 2003; 5(3):115–136.
- Del Viva MM, Igliozzi R, Tancredi R, Brizzolara D. Spatial and motion integration in children with autism. *Vision Res.* 2006; 46(8-9):1242–1252. [PubMed: 16384591]
- Elliott DB, Yang KC, Whitaker D. Visual acuity changes throughout adulthood in normal, healthy eyes: seeing beyond 6/6. *Optom Vis Sci.* 1995; 72(3):186–191. [PubMed: 7609941]
- Field DJ, Hayes A, Hess RF. Contour integration by the human visual system: evidence for a local “association field”. *Vision Res.* 1993; 33(2):173–193. [PubMed: 8447091]
- Heron G, Furby HP, Walker RJ, Lane CS, Judge OJ. Relationship between visual acuity and observation distance. *Ophthalmic Physiol Opt.* 1995; 15(1):23–30. [PubMed: 7724215]
- Hess RF, Dakin SC. Absence of contour linking in peripheral vision. *Nature.* 1997; 390(6660):602–604. [PubMed: 9403687]
- Hess RF, Hayes A, Field DJ. Contour integration and cortical processing. *J Physiol Paris.* 2003; 97(2-3):105–119. [PubMed: 14766137]
- Keita L, Mottron L, Dawson M, Bertone A. Atypical lateral connectivity: a neural basis for altered visuospatial processing in autism. *Biol Psychiatry.* 2011; 70(9):806–811. [PubMed: 21907325]
- Keri S, Kelemen O, Benedek G, Janka Z. Lateral interactions in the visual cortex of patients with schizophrenia and bipolar disorder. *Psychol Med.* 2005; 35(7):1043–1051. [PubMed: 16045070]
- Klein SA. Measuring, estimating, and understanding the psychometric function: a commentary. *Percept Psychophys.* 2001; 63(8):1421–1455. [PubMed: 11800466]
- Kovacs I, Kozma P, Feher A, Benedek G. Late maturation of visual spatial integration in humans. *Proc Natl Acad Sci U S A.* 1999; 96(21):12204–12209. [PubMed: 10518600]

- Milne E, Griffiths H, Buckley D, Scope A. Vision in children and adolescents with autistic spectrum disorder: evidence for reduced convergence. *Journal of autism and developmental disorders*. 2009; 39(7):965–975. [PubMed: 19224351]
- Pointer JS. Habitual vs optimal distance visual acuity. *Ophthalmic & physiological optics : the journal of the British College of Ophthalmic Opticians*. 2008; 28(5):457–466.
- Polat U. Effect of spatial frequency on collinear facilitation. *Spatial vision*. 2009; 22(2):179–193. [PubMed: 19228457]
- Polat U, Sagi D. Lateral interactions between spatial channels: suppression and facilitation revealed by lateral masking experiments. *Vision Res*. 1993; 33(7):993–999. [PubMed: 8506641]
- Polat U, Sagi D, Norcia AM. Abnormal long-range spatial interactions in amblyopia. *Vision Res*. 1997; 37(6):737–744. [PubMed: 9156218]
- Punukollu B, Phelan M. Visual acuity and reported eye problems among psychiatric in-patients. *Psychiatric Bulletin*. 2006; 30(8):297–299.
- Roudaia E, Bennett PJ, Sekuler AB. The effect of aging on contour integration. *Vision Res*. 2008; 48(28):2767–2774. [PubMed: 18831983]
- Salthouse TA, Hancock HE, Meinz EJ, Hambrick DZ. Interrelations of age, visual acuity, and cognitive functioning. *J Gerontol B Psychol Sci Soc Sci*. 1996; 51(6):P317–330. [PubMed: 8931619]
- Schubert EW, Henriksson KM, McNeil TF. A prospective study of offspring of women with psychosis: visual dysfunction in early childhood predicts schizophrenia-spectrum disorders in adulthood. *Acta Psychiatr Scand*. 2005; 112(5):385–393. [PubMed: 16223427]
- Scialfa CT, Cordazzo S, Bubric K, Lyon J. Aging and visual crowding. *J Gerontol B Psychol Sci Soc Sci*. 2013; 68(4):522–528. [PubMed: 23009956]
- Silverstein SM, Kovacs I, Corry R, Valone C. Perceptual organization, the disorganization syndrome, and context processing in chronic schizophrenia. *Schizophr Res*. 2000; 43(1):11–20. [PubMed: 10828411]
- Simmers AJ, Bex PJ. Deficit of visual contour integration in dyslexia. *Invest Ophthalmol Vis Sci*. 2001; 42(11):2737–2742. [PubMed: 11581223]
- Viertio S, Laitinen A, Perala J, Saarni SI, Koskinen S, Lonnqvist J, et al. Visual impairment in persons with psychotic disorder. *Soc Psychiatry Psychiatr Epidemiol*. 2007; 42(11):902–908. [PubMed: 17846698]
- Watson AB, Pelli DG. QUEST: a Bayesian adaptive psychometric method. *Percept Psychophys*. 1983; 33(2):113–120. [PubMed: 6844102]
- Wetherill GB, Levitt H. Sequential Estimation of Points on a Psychometric Function. *Br J Math Stat Psychol*. 1965; 18:1–10. [PubMed: 14324842]
- White C, Brown J, Edwards M. Altered visual perception in long-term ecstasy (MDMA) users. *Psychopharmacology (Berl)*. 2013; 229(1):155–165. [PubMed: 23609769]

Fig. 1. Stimulus and results for contour integration experiment

(A) Subjects attempted to detect the quadrant containing the circular target (shown here at a low noise level). (B) The stimulus display was scaled in size to produce two spatial frequency conditions. (C) The SharpPerceivers could reach threshold accuracy (75%) under noisier conditions than the 20/20 group, especially at high spatial frequencies. Errors equal $\pm$ SEM.

Fig. 2. Stimulus and results for the collinear facilitation (CF) experiment

Orthogonal and collinear elements and thresholds are shown for a (A) lower spatial frequency (4 cycles/deg) and (B) high spatial frequency condition (10 cycles/deg). The task was always to decide whether the central element was visible. Higher thresholds indicate that more target contrast was needed to see the target. Across groups, thresholds were lower for the collinear than orthogonal stimuli, although the 20/20 group required overall more contrast at 10 cycles/deg. Errors equal $\pm$ SEM.