Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

The Neuro-Circular Optotype (NCO): optimizing visual acuity assessment via isotropic spatial-frequency tuning and cortical sparsity

Hossein Peyvandi
Pasargad Institute for Advanced Innovative Solutions (PIAIS)
Abolfazl Moslemi
abolfazl.moslemi14@sharif.edu

Sharif University of Technology (SUT)
Hooman Zolfaghari
Sharif University of Technology (SUT)
Rabee Parhizkari
Sharif University of Technology (SUT)
Maryam Peyvandi
Shahid Beheshti University of Medical Sciences (SBMU)
Maral Talebbeidokhti
Sharif University of Technology (SUT)

Research Article

Keywords: visual acuity, optotype design, logmar, spatial frequency, orientation selectivity, psychophysics

Posted Date: March 30th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9240474/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

The Neuro-Circular Optotype (NCO): optimizing visual acuity assessment via isotropic spatial-frequency tuning and cortical sparsity

Hossein Peyvandi[1], Abolfazl Moslemi[2*], Hooman Zolfaghari[2], Rabee Parhizkari[2], Maryam Peyvandi[3], Maral Talebbeidokhti[2]

[1]Pasargad Institute for Advanced Innovative Solutions (PIAIS), Tehran, Iran.
[2*]Sharif University of Technology (SUT), Tehran, Iran.
[3]Shahid Beheshti University of Medical Sciences (SBMU), Tehran, Iran.

*Corresponding author(s). E-mail(s): abolfazl.moslemi14@sharif.edu;

Abstract

Purpose: To introduce and evaluate the Neuro-Circular Optotype (NCO), a filled-disk visual acuity stimulus with a single calibrated radial gap designed to align more closely with early visual coding principles than conventional optotypes.

Methods: Thirty healthy adults (mean age **24.5±3.2** years) completed adaptive forced-choice acuity testing with Tumbling E, Landolt C, and NCO. NCO and Landolt C were tested in an eight-alternative forced-choice format, whereas Tumbling E was tested in a four-alternative forced-choice format. Thresholds were estimated using a 3-down–1-up staircase and defined as the mean of the final six reversals. Additional experiments assessed recognition accuracy under reduced contrast and Gaussian blur. A computational model consisting of a difference-of-Gaussians retinal/LGN stage and an oriented V1 filter bank was used to compare sparsity and orientation selectivity across optotypes.

Results: NCO yielded better mean acuity thresholds ($\mathbf{-0.08 \pm 0.05}$ **logMAR**) than Landolt C ($\mathbf{-0.01 \pm 0.06}$ **logMAR**) and Tumbling E ($\mathbf{0.04 \pm 0.08}$ **logMAR**). Compared with Tumbling E, the NCO advantage was significant ($\boldsymbol{p < 0.001}$, Cohen's $\boldsymbol{d = 1.2}$); compared with Landolt C, the difference also remained significant ($\boldsymbol{p < 0.05}$, $\boldsymbol{d = 0.6}$). Under degraded viewing, NCO maintained the highest accuracy, including **75.8%** at 20% contrast and **71.2%** with Gaussian blur ($\boldsymbol{\sigma = 2}$ pixels). Tumbling E showed orientation-dependent anisotropy, whereas NCO did not. The computational model suggested that NCO

evoked sparser and more orientation-concentrated responses than the comparison optotypes.
Conclusion: A filled circular optotype with isotropically distributed gap orientations may provide a more robust and neurophysiologically aligned probe of visual resolution than legacy optotypes. Further validation in clinical populations and against standard chart-based outcomes is warranted.

Keywords: visual acuity, optotype design, **logMAR**, spatial frequency, orientation selectivity, psychophysics

Key Points

- The Neuro-Circular Optotype produced better mean acuity thresholds than both Landolt C and Tumbling E in this healthy young adult sample.
- NCO performance was more robust under reduced contrast and blur and showed no measurable orientation bias in this dataset.
- A simple early-vision model suggested that the filled-disk geometry yields sparser and more orientation-concentrated responses than the comparison optotypes.

1 Introduction

Visual acuity (VA) remains a core outcome in clinical eye care and vision research, yet many widely used optotypes were designed primarily for practicality rather than to reflect known properties of early visual coding. Advances in visual neuroscience have shown that threshold perception is strongly shaped by spatial-frequency tuning, orientation selectivity, and contrast sensitivity in the early visual pathway [1–4]. Optotype geometry is therefore not merely a neutral carrier of information; it can influence threshold estimates, response consistency, and robustness under non-ideal viewing conditions.

Conventional optotypes such as the Tumbling E and Landolt C rely on contour arrangements that may overemphasize a limited set of orientations or introduce redundant edge interactions. These properties can amplify anisotropies in performance, especially under blur or astigmatic degradation, and may reduce sensitivity to oblique deficits [5, 6]. In this study, we introduce the Neuro-Circular Optotype (NCO), a filled circular stimulus containing a single calibrated radial gap presented at eight evenly spaced orientations. The design aims to preserve standard acuity calibration while reducing contour redundancy and distributing directional information more isotropically.

The primary objective of this work was to compare NCO with two established optotypes, Landolt C and Tumbling E, using adaptive psychophysical testing in healthy observers. Secondary objectives were to assess robustness under reduced contrast and blur and to interpret the findings using a computational model motivated by retinal/LGN filtering and orientation-tuned cortical responses.

2 Methods

2.1 Study design

This was a repeated-measures psychophysical study in which each participant completed visual acuity testing with three optotype classes: Tumbling E, Landolt C, and NCO. Threshold-based testing was supplemented by degradation experiments and computational modelling.

2.2 Participants

Thirty healthy volunteers (16 female, 14 male; mean age 24.5±3.2 years) participated. Eligibility criteria included best-corrected VA of ≤ 0.0 logMAR, astigmatism < 0.50 D, and no known ocular or neurological disease. All participants provided written informed consent before testing.

2.3 Stimulus design

Each NCO stimulus consisted of a filled black disk containing a single radial gap. Unlike annular or outline-based optotypes, the filled geometry was intended to retain stable low-to-mid spatial-frequency content while preserving a directional discontinuity that could be resolved through the gap. The gap was presented at eight equally spaced orientations (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°), creating an eight-alternative forced-choice (8AFC) task. Representative NCO stimuli are shown in Fig. 1.



Fig. 1 Representative Neuro-Circular Optotype stimuli showing the filled-disk geometry with calibrated radial gaps presented at different orientations

Stimuli followed conventional logMARscaling. At 0.0 logMAR, the gap width subtended 1 arcminand the overall optotype diameter subtended 5 arcmin. For logMARlevel L,

$$\mathrm{MAR}(L) = 10^{L} \text{ arcmin}, \qquad \mathrm{Diameter}(L) = 5 \times 10^{L} \text{ arcmin}. \tag{1}$$

2.4 Display calibration and viewing geometry

Stimuli were presented using PsychoPy on a calibrated IPS display with 1920×1080 pixel resolution and a 60 Hz refresh rate. Background luminance was maintained at 150 cd/m^2 and gamma correction was applied ($\gamma = 2.2$). Participants viewed the display binocularly from 300 cm using a chin rest.

If display pixel pitch is denoted by p (cm/pixel) and viewing distance by D (cm), the visual angle per pixel is approximated by

$$\alpha_{\mathrm{pix}} \approx \arctan\left(\frac{p}{D}\right) \cdot \frac{180}{\pi} \cdot 60 \quad \text{arcmin/pixel.} \tag{2}$$

The corresponding rendered dimensions at acuity level L are

$$w_{\mathrm{gap}}(L) \approx \frac{10^{L}}{\alpha_{\mathrm{pix}}}, \qquad d_{\mathrm{opt}}(L) \approx \frac{5 \cdot 10^{L}}{\alpha_{\mathrm{pix}}}. \tag{3}$$

Trials for which the computed gap width fell below 1.5 pixels were excluded from threshold estimation to reduce pixel-quantization artefacts.

2.5 Control optotypes

Two established comparator stimuli were used. Landolt C was presented with the same eight orientations as the NCO in an 8AFC format. Tumbling E was presented in its conventional four-alternative forced-choice (4AFC) format with up, down, left, and right orientations.

2.6 Psychophysical procedure

Each trial began with a central fixation interval of 500 ms, followed by stimulus presentation for 1500 ms and then a 300 ms inter-trial interval. Participants responded via keypad. The response set consisted of eight keys for NCO and Landolt C and four keys for Tumbling E.

Thresholds were obtained using a 3-down–1-up staircase targeting 79.4% correct performance. Three consecutive correct responses decreased optotype size, and one incorrect response increased size. The step size was 0.10 log units until two reversals and 0.05 log units thereafter. Each staircase terminated after 12 reversals, and threshold was defined as the mean of the final six reversals. Optotype block order was counterbalanced across participants using a Latin-square design, and orientations within each block were randomized.

2.7 Degradation conditions

Robustness testing was conducted under two forms of stimulus degradation: reduced contrast and optical blur. Michelson contrast was reduced from 100% to 20%. Blur was simulated by applying a Gaussian kernel with standard deviation $\sigma = 2$ pixels.

2.8 Data preprocessing

Trials with missing responses were removed. For response-time analyses, within-subject outliers exceeding ± 2 standard deviations were excluded. Participants with incomplete blocks or overall accuracy below 50% in any 8AFC condition were to be excluded; no participant met these criteria.

2.9 Computational model

To provide a mechanistic interpretation of optotype differences, we implemented a two-stage model. The first stage used difference-of-Gaussians filters to approximate center–surround responses in the retina and lateral geniculate nucleus. The second stage applied a bank of oriented Gabor-like filters to approximate V1 simple-cell responses. Population output was summarized using Hoyer sparsity, orientation-energy concentration, and decoding performance for gap-direction estimation.

2.10 Statistical analysis

Repeated-measures data were analysed using linear mixed-effects models to account for within-subject dependence. The primary outcome was logMARthreshold. Secondary outcomes included identification accuracy and response time. The general model form was

$$y \sim \text{Optotype} + \text{Orientation} + \text{Condition} + (1|\text{Subject}), \tag{4}$$

where y denotes the outcome of interest. Fixed-effect contrasts were tested with associated p values, and effect sizes were reported as Cohen's d or standardized coefficients where applicable. Holm correction was applied to multiple comparisons.

3 Results

3.1 Acuity thresholds

The NCO produced the best mean acuity threshold of the three stimuli, with a mean of -0.08 ± 0.05 logMAR(95% CI: -0.10 to -0.06). The corresponding means for Landolt C and Tumbling E were -0.01 ± 0.06 logMARand 0.04 ± 0.08 logMAR, respectively. Relative to Tumbling E, the NCO advantage was statistically significant ($p < 0.001$, Cohen's $d = 1.2$). The difference between NCO and Landolt C was also significant ($p < 0.05$, $d = 0.6$).

Table 1 Acuity and performance summary for the three optotype conditions

Optotype	Acuity (logMAR)	Accuracy (%)	Response time (ms)
Tumbling E	0.04 ± 0.08	88.3	790 ± 120
Landolt C	-0.01 ± 0.06	90.6	730 ± 105
NCO	$\mathbf{-0.08 \pm 0.05}$	**93.8**	$\mathbf{695 \pm 95}$

3.2 Orientation dependence

Mixed-effects analyses indicated a significant orientation effect for Tumbling E ($F(7, 203) = 4.5$, $p < 0.01$), consistent with orientation anisotropy. In contrast, the corresponding effect for NCO was not significant ($F < 1$, $p > 0.1$), suggesting approximately isotropic performance within this sample.

3.3 Robustness under contrast reduction and blur

NCO showed the highest identification accuracy under both degradation conditions. At 20% contrast, mean accuracy was 75.8% for NCO, 69.1% for Landolt C, and 65.2% for Tumbling E. Under Gaussian blur with $\sigma = 2$ pixels, mean accuracy was 71.2% for NCO, 64.7% for Landolt C, and 61.4% for Tumbling E (Table 2; Fig. 2).

Table 2 Identification accuracy under degradation conditions

Optotype	Accuracy at 20% contrast	Accuracy with blur ($\sigma = 2$ px)
Tumbling E	65.2%	61.4%
Landolt C	69.1%	64.7%
NCO	**75.8%**	**71.2%**

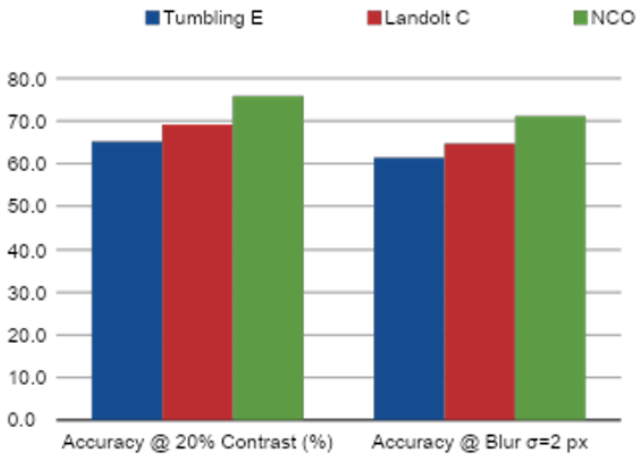


Fig. 2 Identification accuracy under degradation conditions for the three optotype classes under reduced contrast and Gaussian blur

3.4 Computational modelling results

The modelling analysis suggested that NCO produced sparser and more orientation-specific population responses than either Landolt C or Tumbling E. Relative to the comparison optotypes, NCO generated a more localized discontinuity signal with less diffuse activation across orientation channels, consistent with the hypothesis that the filled-disk geometry reduces cross-orientation masking. Representative model outputs for Landolt C, NCO, and Tumbling E are shown in Figs. 3–6.

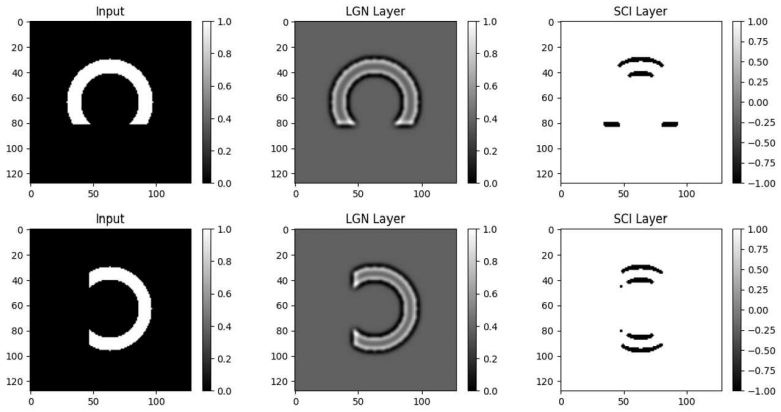


Fig. 3 Representative computational model output for Landolt C showing the input stimulus, the LGN-like response, and the orientation-selective cortical response

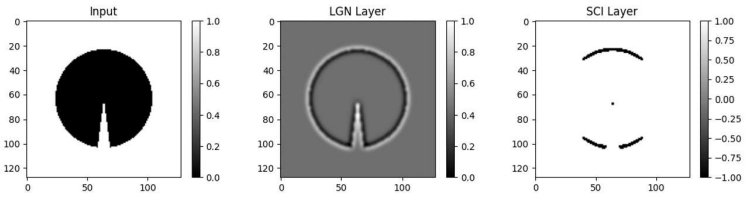


Fig. 4 Representative computational model output for a cardinal-orientation Neuro-Circular Optotype showing a compact directional discontinuity signal and comparatively localized orientation-selective responses

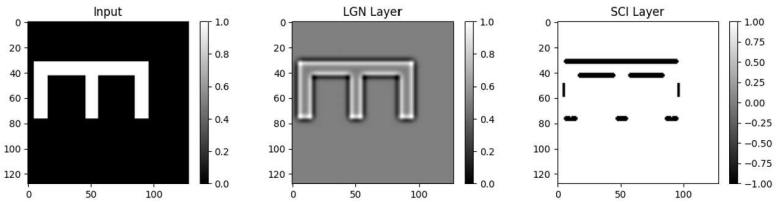


Fig. 5 Representative computational model output for Tumbling E showing more spatially distributed edge structure and broader activation across orientation channels

4 Discussion

This study evaluated a new optotype geometry motivated by established properties of early vision. The principal finding was that the NCO yielded better mean acuity thresholds than both Landolt C and Tumbling E in a healthy young adult sample. The NCO also showed higher identification accuracy under reduced contrast and blur and did not exhibit measurable orientation dependence in the present dataset.

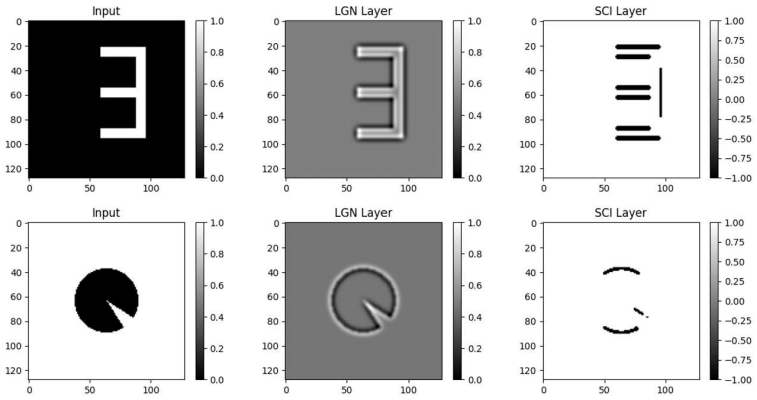


Fig. 6 Comparison of model outputs for Tumbling E and an oblique-orientation Neuro-Circular Optotype showing the more localized and orientation-specific response pattern for NCO in the illustrated example

A plausible explanation is that the filled-disk geometry provides a more stable low-to-mid spatial-frequency carrier while the radial gap supplies a compact directional cue. In contrast, multi-stroke and contour-heavy optotypes may introduce additional edge interactions that become more detrimental when optical quality is reduced. This interpretation is supported by the computational model, which suggested that NCO evokes a sparser and more orientation-concentrated neural response pattern.

These results may have practical implications for both laboratory and digital vision testing. Reduced anisotropy may be advantageous when screening for orientation-specific visual deficits, and the solid geometry may be less vulnerable to display aliasing than letter-like stimuli with multiple limbs. Because the NCO retains standard logMARscaling, its thresholds remain interpretable within established acuity frameworks.

Several limitations should be considered. First, the study included only young healthy adults, so the clinical utility of NCO remains to be established in populations with refractive error, cataract, amblyopia, or retinal disease. Second, the comparison with Tumbling E is conservative but not perfectly psychometrically matched because the response format differed (4AFC versus 8AFC). Third, several operational details required for full clinical translation, such as normative datasets, chart implementation, and calibration against ETDRS-style outcomes, remain to be developed. Future work should test NCO in larger and more heterogeneous cohorts and evaluate test–retest reliability, clinical agreement, and performance in real-world digital platforms.

5 Conclusion

The Neuro-Circular Optotype combines conventional logMARcalibration with a geometry designed to align more closely with early visual coding principles. In this initial study, it produced better mean thresholds and greater robustness under degradation

than two established comparator optotypes. These findings support further evaluation of NCO as a biologically informed alternative for next-generation visual acuity assessment.

Acknowledgements. We thank the study participants for their time and effort.

Declarations. Funding No funds, grants, or other support were received for the conduct of this study.

Competing interests We declare that they have no competing interests.

Ethics approval This study involving human participants was performed in accordance with the ethical standards of the institutional and national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. The study protocol was approved by the relevant institutional review board or ethics committee.

Consent to participate Written informed consent was obtained from all individual participants included in the study.

Consent for publication Not applicable.

Data availability The datasets generated and/or analysed during the current study are not publicly available because they contain participant-level psychophysical observations, but de-identified data are available from the corresponding author on reasonable request, subject to approval by the authors and any applicable ethics or privacy restrictions.

Code availability Custom code used for stimulus generation, psychophysical testing, and computational modelling is available from the corresponding author on request.

Author contributions Hossein Peyvandi: conceptualization. Abolfazl Moslemi and Hooman Zolfaghari: data collection. Abolfazl Moslemi and Rabee Parhizkari: formal analysis. Maryam Peyvandi: clinical oversight. Abolfazl Moslemi, Maral Talebbeidokhti: computational modelling. All authors read and approved the final manuscript.

References

[1] Campbell FW, Robson JG. Application of Fourier analysis to the visibility of gratings. J Physiol. 1968;197(3):551–566. https://doi.org/10.1113/jphysiol.1968.sp008574

[2] Hubel DH, Wiesel TN. Receptive fields and functional architecture of monkey striate cortex. J Physiol. 1968;195(1):215–243. https://doi.org/10.1113/jphysiol.1968.sp008455

[3] Ferster D, Miller KD. Neural mechanisms of orientation selectivity in the visual cortex. Annu Rev Neurosci. 2000;23:441–471. https://doi.org/10.1146/annurev.neuro.23.1.441

[4] Olshausen BA, Field DJ. How close are we to understanding V1? Neural Comput. 2005;17(8):1665–1699. https://doi.org/10.1162/0899766054026639

[5] Bondarko VM, Danilova MV. What spatial frequency do we use to detect the orientation of a Landolt C? Vision Res. 1997;37(15):2153–2156. https://doi.org/10.1016/S0042-6989(97)00005-4

[6] Sanchis-Jurado V, Cerviño A, Villa-Collar C, Jordá P, Mallen EAH. The effect of induced astigmatism on visual acuity measurement with different optotypes. J Optom. 2017;10(4):230–236. https://doi.org/10.1016/j.optom.2016.09.001

[7] Bailey IL, Lovie JE. New design principles for visual acuity letter charts. Am J Optom Physiol Opt. 1976;53(11):740–745. https://doi.org/10.1097/00006324-197611000-00006

[8] Ferris FL III, Kassoff A, Bresnick GH, Bailey I. New visual acuity charts for clinical research. Am J Ophthalmol. 1982;94(1):91–96. https://doi.org/10.1016/0002-9394(82)90197-0

[9] Bailey IL, Lovie-Kitchin JE. Visual acuity testing. From the laboratory to the clinic. Vision Res. 2013;90:2–9. https://doi.org/10.1016/j.visres.2013.05.004

[10] Chariker L, Shapley R, Young LS. Orientation selectivity from very sparse LGN inputs in a comprehensive model of V1 cortex. J Neurosci. 2016;36(49):12368–12384. https://doi.org/10.1523/JNEUROSCI.2058-16.2016

[11] Stanley GB, Jin J, Wang Y, Desbordes G, Wang Q, Black MJ, Alonso JM. Visual orientation and direction selectivity through thalamic synchrony. J Neurosci. 2012;32(26):9073–9088. https://doi.org/10.1523/JNEUROSCI.4968-11.2012