Curvature formation in the visual cortex: How do we sample?

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Does the human visual system sample shapes at discrete points? During adaptation when the neurons are fatigued, one observes the underlying principles that were once less prominent than the fatigued features. Operating under deficit, these less prominent features expose the original contributions from the fatigued neurons that are now absent. An underlying lower order neural process, is thus, now revealed. In this paper, we conduct experiments using a modified version of the circle-polygon illusion in order to reveal the brain's sampling pattern. The circle-polygon illusion produces polygonal percepts during adaptation when a static dark outline circle is pulsed at 2 Hz alternating with a gradient luminance circle. We perform two experiments. In the first experiment, we present circles of size [2,4,8,16] deg presented at eccentricity [0,1,2,4,8] deg in a cross design. In the second experiment, we modify the method of Sakurai (2014) and display arc lengths that are 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, 7/8 and 1 (whole) of a circle, of size 4 and 8 deg, presented centrally. The observers report the edge length seen instead of a polygon order. We find that the stimulus size and presentation eccentricity, taken together, best explain the edge length reported by the users and that size alone is the most reasonable fixed parameter. The users, as a random effect, do not influence the mean of the edge length reported when considering the best model reported (size and eccentricity together) according to loglikelihood. However, the users do influence edge length reported only when using mean eccentricity or eccentricity as the parameter influencing edge length. Arc lengths of a circle produce same or similar edge lengths. The length of the curve does not play a significant role signifying that biological neurophysiology at an eccentricity controls the edge length formation.

Keywords: shape adaptation, cortical adaptation

Introduction

Adaptation is a process by which a set of population neurons are fatigued, thereby allowing other sets of neurons that encode inhibition and are not fatigued, to reveal their neural preference for structure and shape. Indirectly, it also reveals the original coding

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that is now absent. In an earlier experiment (Nisar & H. Elder,2021), different regular polygons of varying order were observed during in-place adaptation when a flashing circle was alternated with its black outline at 2Hz. In this study, we alter the stimuli and probe if the arc length of the stimulus effects the edge length seen and reveals sampling patterns for curvature closure. We keep in mind the importance of *connectedness* and therefore use arc lengths as the probing parameter. We use edge lengths instead of polygon order to probe the importance of edges versus overall shape.

Both the contour type and its angular orientation are important descriptors for shape selectivity (Pasupathy & Connor,1999,2001;El-Shamayleh & Pasupathy,2016). In other words, the higher part of the ventral system encodes higher order contour derivatives in the form of tuning for broad curvature as well as certain sharp narrow curvature. (El-Shamayleh & Pasupathy,2016) show the existence of normalized curvature supported by neurons that fire such that the overall angle subtended by the contour at the center remains the same. However, there has been little study done to vigorously study the simplest convex shape, the circle, and arc lengths that are part of its circumference, under adaptation, and reveal the encoding at lower levels of the visual cortex. This angle-preserving coding for curvature in mid-level vision might also exist in early visual cortex through the organization of receptive fields within the cortical column allowing long range connections to build edge lengths of fixed orders at a specified eccentricity.

We hypothesize that the brain may sample in a predictable way. We know that the sampling is a by product of closure (MacLeod & Ellis,1939;Wertheimer,2007), Wertheimer(1912,1923) from Gestalt theory and also a neuro-physiologically mapping of the arrangement of the receptive fields that may give rise to emergent contours (Gilbert,1992;Li, Piëch, & Gilbert,2008). In (Nisar & H. Elder,2021), in-place adaptation polygons were observed from flashing circles. They were reported to be symmetrical regular polygons, changing strength and polygon order with changing presentation eccentricity and stimulus size. The strength was strongest when the circle was of size 1 degree visual angle and was presented at an eccentricity 8 degree visual angle. The largest polygon order was observed when the percept was of size 8 and at eccentricity 4 degree. The variation in polygon order showed that the lower level account of human vision was scale-variant. We want to test if the brain codes for edge length at a particular eccentricity in fixed lengths. One way to test this is by varying the arc lengths progressively.

We construct two sets of experiments. The first experiment presents full circles with diameter [2,4,8,16] $^\circ$ and at eccentricity [0,1,2,4,8] $^\circ$ in a cross design. The second experiment presents arc lengths, that are 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, 7/8 and 1 (whole) of the circumference of the circle, of diameter [4,8] respectively, presented at eccentricity 0. We ask the following questions: (a) How does the edge length and strength of percept change with size? (b) How does the edge length and strength of the percept change with eccentricity? (c) How does the edge length and strength of the percept change with size and eccentricity? (d) Can we build a linear mixed model to characterize the best fit model from the responses collected? (f) Do participants effect the models? (g) Does M-scaling play a role in predicting the edge length reported? (g) Does the edge length change with changing arc lengths when the circle from which they are generated remains the same?

The key motivation for recording edge lengths was to see if there is a difference between (polygon order) shape and perceived edges. Homomorphic class differences are processed earlier and outside the ventral stream. This is revealed in several psycho-physical experiments by Chen and Palmer (Chen,1982;Palmer & Rock,1994). Chen states that connectedness, closed or open, and the number of

holes are topological features that form important perceptual representations that are extracted early in the visual process (Chen,1982). Palmer in (Palmer & Rock,1994) show that uniform connectedness is a property where regions of similar lightness, colour or texture are perceived as single units even before grouping principles such as proximity and similarity begin to take effect. Edge length, also defined as the gap between contours, allows the construction of closed shapes if they are small (Elder & Zucker,1993). This property is called closure. Closure is often thought to be a primitive property, separate from the ventral stream pathway that culminates in the inferotemporal region (IT) that makes inferences about global shape from earlier components. Wertheimer's earliest experiments in psychology (Wertheimer,2007) assert that the quality of the part is a function of its integration in the whole. In other words, the whole is more significant and determines the quality of the part. The paradigm of global or local shape are competing features in defining shape (Kimchi,1992). We, therefore, study edge formation from arc lengths as a corollary to the polygons reported to see if in-place adaptation to part shapes are different from full circular shapes and if they are effected by processes outside the ventral pathway that contains the visual cortex and its early region, V1 .

Methods

Observers

30 observers participated in the experiment. All observers participated in the online version of the experiment, hosted on Pavlovia. Participants were recruited using Prolific, an online recruitment site. The participants were screened for being fluent in English and for having corrected-to-normal vision.

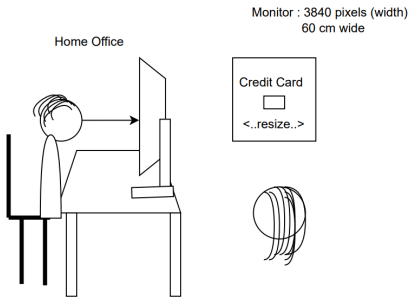
Apparatus

Observers were asked to have a measuring tape for the experiment or discontinue if they did not. They were asked to confirm that they had a monitor screen of atleast 13 inches (or 33 cm) wide and to adjust the chair such that the screen was at a comfortable viewing distance.

To ensure that the correct size and eccentricity of the stimuli was being generated, a set of instructions were displayed at the start of the experiment. The participant reported the viewing distance by measuring the distance (in centimeters) between the bridge of their nose and the center of the screen.

The participants were asked to scale a virtual credit card on their screen to fit a physical credit card that they placed against the screen. Pixels per degree was computed by using the scaled card information (in pixels) and the distance of the participant from the monitor. The size of the stimuli, in degrees and its eccentric placement, was computed and drawn using the pixels per degree information.

Other components of the instruction included asking the participant to dim the lights. The background of the experiment was white. The mean luminance of the monitor was expected to read 26 cd/m^2.



(a)

(b)

Figure 1: (a) Observers were asked to have a tape measure handy and measure their distance from the center of the screen. (b) Participants were asked to scale the virtual credit card, using the arrow keys, such that it matches the length and width of standard credit card that is placed sgainst the screen. A standard credit card is 8.5 cm wide and 5.4 cm high.

Measurement Techniques

Participants were instructed to provide their viewing distance in centimeters using a measuring tape and scale a credit card to match a physical credit card. The participants indicated the polygon to which they adapted by selecting the edge length in an array of edge lengths during the response selection phase. A standard mouse was assumed to be used to point and click on the edge length since the participants were online. Unlimited time was awarded to select an edge length. Once the edge length was selected, a Likert scale from 1 to 10 was shown to mark the strength of the percept if the participants had indicate a somewhat polygonal percept. Once the participant recorded a response, the next stimuli presentation appeared.

Experiment 1

The experiment reports the edge length of the polygon percept seen as the circle diameter and eccentricity of the circle's placement varies. We present stimuli that are circles and alternate with a circle that is its inward gradation pattern. The diameter of the circles we present as stimuli, subtend a visual angle of 2,4,8 and 16 ° on the user's eye. The eccentricity at which the circle center is presented is at 0,1,2,4 and 8 °. There were a total of 36 unique stimuli presentations when accounting for the size, eccentricity and the handedness of the stimuli appearance from the fixation cross (left or right). We study the adaptation produced in place, induced by the flashing stimuli, at varying eccentricities along the horizontal meridian and report the resulting polygonal percepts that form. We do not measure the polygon order directly. Instead we use edge lengths that would represent the regular polygon. Participants mark an edge length of the polygon percept they see. The url for the experiment is available at *https://run.pavlovia.org/inisar2/fragmentonline30*.

Stimuli

The stimuli consisted of a circle with a black outline that alternated with another circle of the same size but with an inward gradation pattern. The black outlines were constructed of penwidth 5 using Psychtoolbox. See Figure 2(b). The circles were built of different

sizes. See Figure 2(a). The eccentricity at which the circle was presented was 1,2,4 and 8 °. Randomized trials presented every combination of the circle radius and its eccentricity. Every unique combination of eccentricity and radius was presented ten times for a total of 360 trials. The circle was placed left of the central fixation cross half the time and on the right of the fixation cross half of the time. The stimuli was presented against a white background.

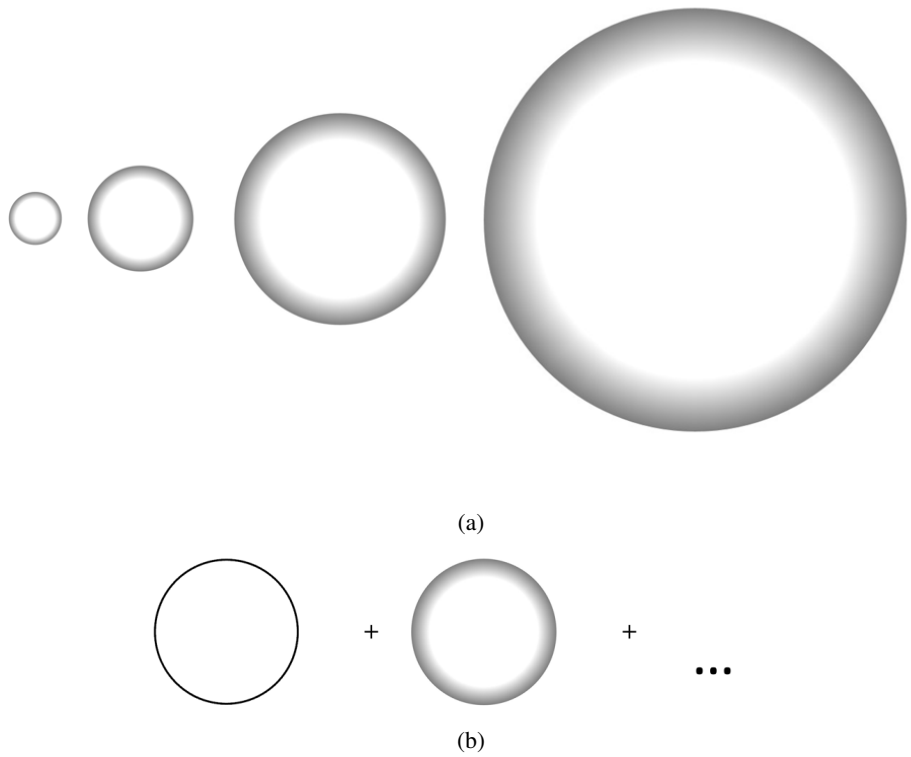


Figure 2: Experiment 1: (a) Stimuli sizes: Circles with inward gradation, whose diameter subtends 2,4,8 and 16 degrees of visual angle respectively on the user's eye. The pictures are for illustration only and show the relative sizes of the stimuli. Stimuli do not subtend the exact degree on the user's eye. (b) Flashing stimuli: Circle in a black outline and its inward gradation. The outline and the inward gradation alternate at 2 Hz. The circle is presented to the left of the fixation cross.

Experiment 2

In this experiment, we construct several circular arc lengths. The arc lengths are 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, 7/8 and 1 (or whole) of a circle. The circle stimuli are of size 4 deg and 8 deg visual degree angle presented centrally. In this experiment we probe the edge length seen during adaptation using the arc length of the circle. The url for the experiment is available at *https://run.pavlovia.org/inisar2/fragmentonline29*.

Stimuli

The stimuli consisted of a circle with a black outline that alternated with another circle of the same size but with an inward gradation pattern. See Figure 3. The stimuli were arc lengths of a circle. The arc lengths were 1/8,1/4,3/8,1/2,5/8,3/4,7/8 and the whole of a circle. Two stimuli sizes were used. One was a size of 4 ° and the other was a size of 8 °. There were a total of 16 unique stimuli when

allowing both size and arc length. All stimuli were presented at 0 ° eccentricity. The black outlines were constructed of pen width 5 using Psychtoolbox. The renderings were hosted on Pavlovia. Randomized trials presented each stimulus 10 times. There were a total of 160 trials. Participants were allowed 16 practice trials.

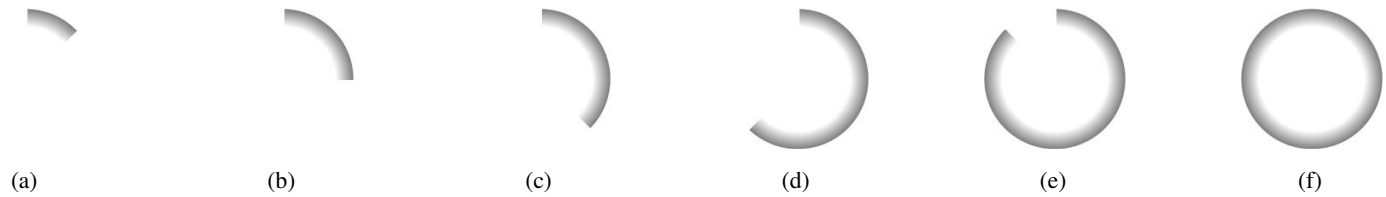


Figure 3: Experiment 2: (a) Arc length that is 1/8 of a circle (b) Arc length that is 1/4 of circle (c) Arc length that is 3/8 of a circle (d) Arc length that is 5/8 of a circle (e) Arc length that is 7/8 of a circle. Half and three-quarters of a circle are left out of the figures for brevity.

Procedure

Experiment 1

The eccentricity at which the circle center is presented is at 0,1,2,4 and 8 °. There were a total of 36 unique stimuli presentations when accounting for the size, eccentricity and the handedness of the stimuli appearance from the fixation cross (left or right). The circles were presented at random orientations during the trial. In each trial, the circle with the outline flashed with its graded luminance at 2Hz for 10 seconds.

20 practice trials were offered for an estimated time of 4 minutes. After the practice session, the participants were presented 220 trials in blocks of 22 stimulus for a total of 10 blocks. The entire recorded experiment took 55 minutes, discounting voluntary breaks.

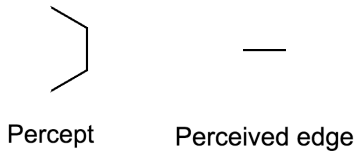
Experiment 2

There are 16 distinct stimuli presentations. Each circle has 8 different arc length configurations and the circle are of two different sizes: 4 ° and 8 °. The circles were presented at random orientations during the trial. In each trial, the circle with the outline flashed with its graded luminance at 2Hz for 10 seconds.

A complete set of 16 practice trials were offered for an estimated time of 3 minutes. After the practice session, the participants were presented 160 trials in blocks of 16 stimulus for a total of 10 blocks. The entire recorded experiment took 45 minutes, discounting voluntary breaks.

Procedure for both experiments

The participants were asked if the stimulus seen was purely circular or somewhat polygonal. If the participants indicated it was somewhat polygonal, they were then asked to judge the perceived edge length and the strength of the percept. The perceived edge lengths were displayed as a series of eighteen line segments built from the equation $log(a * b^c)$ such that $a = 1$ and $b = 0.9$. c belonged to the range $[1, 20]$ and each value of c gave rise to a unique line segment. The difference between the line lengths, when they were represented in their log formats, was uniform. The shortest line segment subtended 0.105 ° visual angle on the eye whereas the largest line segment subtended 2.107 ° visual angle on the user's eye.

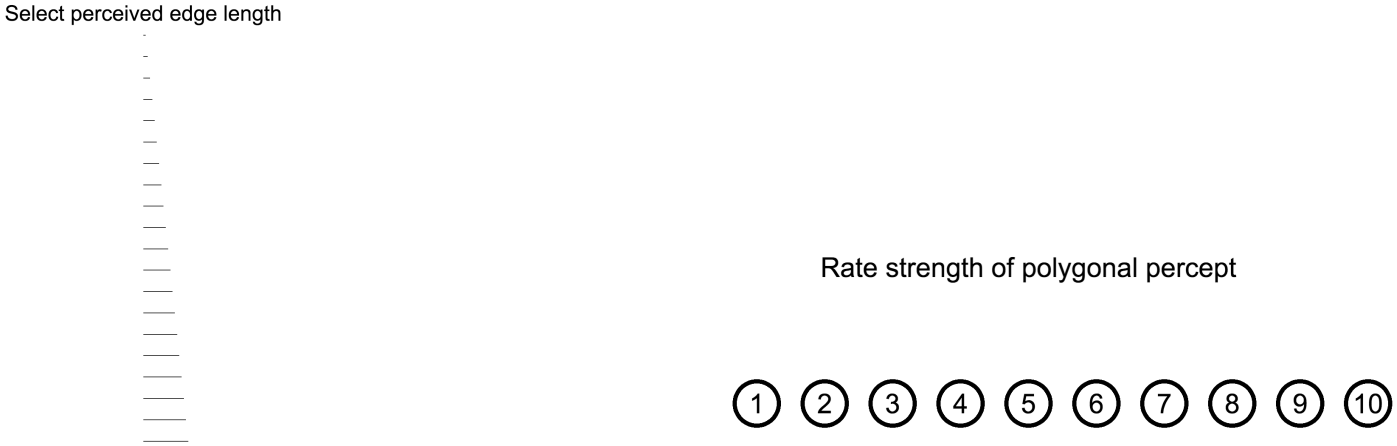


(a) (b)

Figure 4: (a) Percept shown in the experiment brief (b) Perceived edge that the participant would have to mark was shown to the participants.

Prior to starting the experiment, the observers were briefed with the following instruction:

"After the first phase of the trial, you will be asked if you saw a perfect circle or a polygonal percept. If you perceived the shape as somewhat polygonal, you will indicate the perceived length of the polygonal edges. An example of the polygon seen and the corresponding edge length that you will mark is shown on the right. If you indicated a polygon percept, you will indicate the strength of the polygon percept on a scale from 1 (very weak) to 10 (very strong). "



(a) (b)

Figure 5: (a) Users were asked to select the perceived edge from an array of uniformly incremented log-length lines. (b) Users were asked to rate the strength of the polygonal percept from 1-10.

The participants were asked for their viewing distance from the screen by measuring and reporting the distance (in centimeters) between the bridge of their nose and the center of the screen.

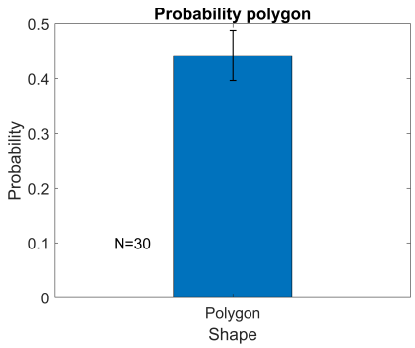
To ensure that the stimuli were the right size, the participants were asked to scale an image of a credit card displayed on the screen till it matched a physical credit card using the arrow keys. The scaling allowed the computation of pixels per degree for the participant's monitor screen and the appropriate display of the stimuli in degrees thereafter.

Results from Experiment 1

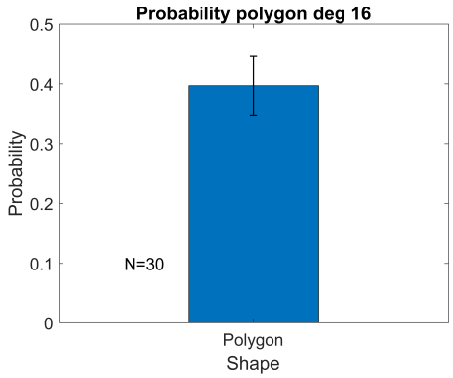
Shape

The results from the 30 observers are shown in the graphs below. Most observers reported circles than polygons. Significantly enough reported edge lengths during online experiments to allow the hypothesis that polygonal percepts are seen during online adaptation.

Retinotopical organization in human vision is such designed that the density of the lateral ganglion cells decline in peripheral vision and the receptive fields become larger (Daniel & Whitteridge,1961;Van Essen, Newsome, & Maunsell,1984,2002). This would support the hypothesis that less 'shape' is seen in the periphery. This theory is supported by the behaviour responses that show a decline in the polygons reported as the stimuli moves from the fovea to the periphery. Despite the idea of a point image scaling by a cortical magnification onto the visual cortex, such that the magnification remains the same, the amount of 'shape' or polygon reported changes with eccentricity.



(a)



(b)

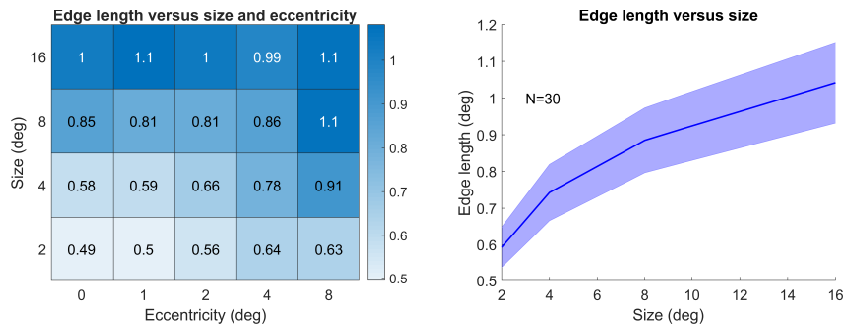
Figure 6: Probability circle seen versus polygons. This shows that polygon are still reported as a phenomenon during in-place adaptation while running experiments online. (a) Probability of seeing polygons over all eccentricities and all stimulus sizes (b) At a large eccentricity of 16 deg, the probability of seeing polygons was much lower than that reported at smaller eccentricities.

One-way Anova across sizes but at fixed eccentricity shows that the differences in the mean probability of polygons reported are significant across the subjects at eccentricity 0 ° and 8 ° and there is significant mean differences across the subjects when considering any stimuli size. However, a decrease in polygons is seen at a larger eccentricity (16 °) and there is a general decline in the polygon reported as the eccentricity increases.

Edge Length

The edge length decreases with increasing stimulus size, measured in °, and increases with eccentricity. See Figure 7 (a,b), 8(a).

Stimuli is presented at a given eccentricity and for a particular degree visual angle size. Because the stimuli can be quite large and may have peripheral influences from its own shape effecting in-place adaptation, we further study the edge length as a function of minimum eccentricity and mean eccentricity. While minimum eccentricity is rather straightforward and understood as the minimum eccentricity that any part of the stimulus might be presenting itself to the participant, mean eccentricity can be seen as the eccentricity

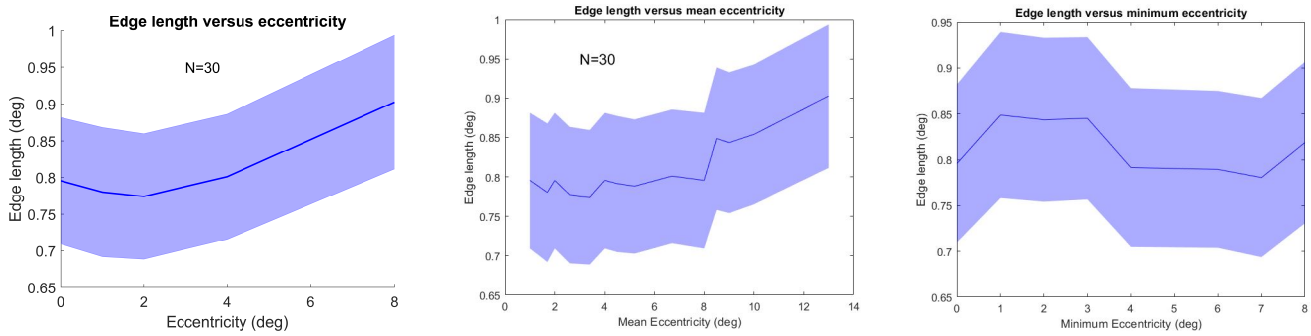


(a) (b)

Figure 7: (a) Mean edge length (in deg) for different sizes of the circle stimuli: 2, 4, 8 and 16 , presented at different eccentricities of 0,1,2,4 and 8 degrees. (b) Edge length versus size
Edge length increases slightly with size (diameter) and also with eccentricity. Size has a larger effect. Eccentricity has a more moderate effect. The edge length is a mean computed over all participants for the given size and eccentricity in (a) and at given size in (b).

that is the summation of the eccentricity at points around the circle, given by the following equation,

$$\int_0^{2\pi} \sqrt{(x_o + Rcos(t))^2 + R^2 sin^2 t} \tag{1}$$



(a) (b) (c)

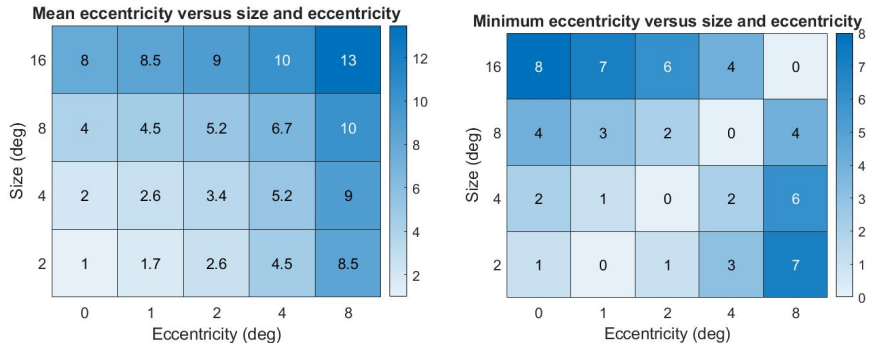
Figure 8: (a) Edge length versus eccentricity (b) Edge length versus mean eccentricity (c) Edge length versus minimum eccentricity
Edge length increases slightly with size and also with eccentricity. Size has a larger effect. Eccentricity has a more moderate effect. The means are computed over all participants.

Strength

The experiment measured the strength of the percept on a scale from 1 to 10. 0 meant that the observer did not see a polygon percept after adaptation. The percept in this case remained the same as the circular stimuli. A 10 on the scale indicated a crisp regular polygon. The strongest effect is for small objects at large eccentricities. See Figure 10 (b). Large objects at small eccentricities and small objects at large eccentricities produce large effects. Small objects at small eccentricities and large objects at large eccentricities produce smaller effects. This is demonstrated in the matrix in Figure 10 (a).

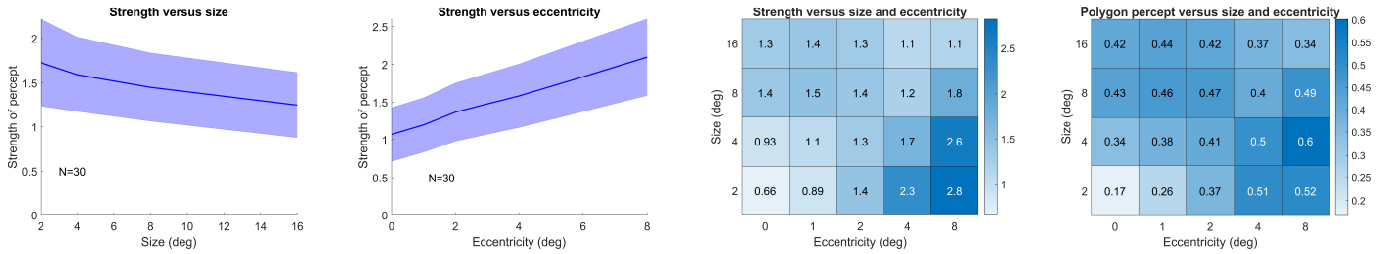
Eccentricity

Eccentricity has a modest effect on the edge length reported. Proximity to the fovea shows higher order polygons and thus shorter



(a) (b)

Figure 9: (a) Mean eccentricity shown as a function of size and eccentricity (b) Minimum eccentricity shown as a function of size and eccentricity. (a) accompanies mean eccentricity referenced in Figure 8(b) and (b) accompanies minimum eccentricity referenced in Figure 8(c).



(a) (b) (c) (d)

Figure 10: (a) Strength versus size (b) Strength versus eccentricity (c) Strength decreases with size and increases with eccentricity. Size has a larger effect. Eccentricity has a more moderate effect. (d) Probability polygon percept as a function of size and eccentricity

edge lengths. See Figure 8(b).

Model that explains the edge length observed

Can the edge length observed be explained by a retinal model or a higher level cortical model? A retinal function samples the circular stimulus in 2D eccentric cartesian coordinates. We fit a first order linear model of the edge length as a function of the retinal size and another as a function of the cortical circumference size. We shall hereby call the retinal circumference size, retinal length, and the cortical circumference size, cortical length. The functions for edge length as a function of the retinal length and the cortical length is given below in Equation 2 and Equation 3. Equation 2 describes x as retinal circle circumference whereas Equation 3 describes x as cortical circle circumference.

$$y = 0.309 + 0.00198 * x \tag{2}$$

$$y = 0.296 + 0.00175 * x \tag{3}$$

The M-scaling ratio between the experimental cortex and the retinal scaling is 1.15. This is across all eccentricities. The M-scaling ratio between the experimental cortex and the retinal scaling, following Rovamo and Virsu (Rovamo & Virsu,1979), averaged over eccentricities, is 4.4, suggesting that the scaling observed during adaptation does not necessarily follow neuro-physiological ground truth values. This illustrates the fact that even though neurophysiology might predict shape formation, the mechanistic observation of curvature is subjective.

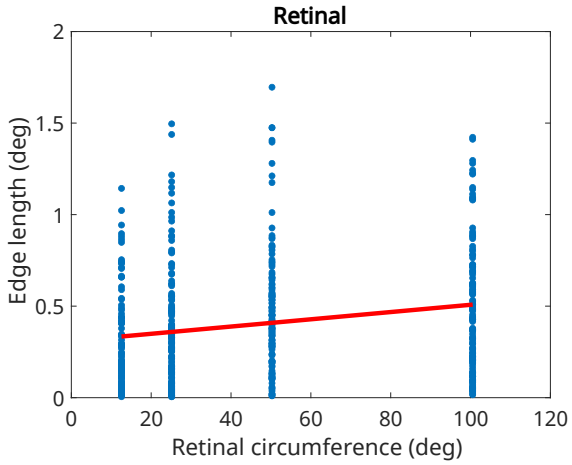
Figure 12(d) shows how the cortical magnification factor obtained from psychophysical recording differs from that measured by Rovamo and Virsu's measured neurophysiological recordings.

The cortical length can be computed from the points seen on the circle seen on the 2D retinal plane and after applying the cortical M-scaling that measures mm of cortex per degree of visual angle, as a function of eccentricity, on those sampled 2D points. The cortical mapping function can be built as follows: (a) create a tangent at sample points on the stimuli circle seen in the retinal 2D plane (b) The tangent is then used to compute the speed on the curve (c) The cortical magnification factor is multiplied by the speed and the small sample step size to get the cortical length traced on the cortex. For a detailed description, see Table 1.

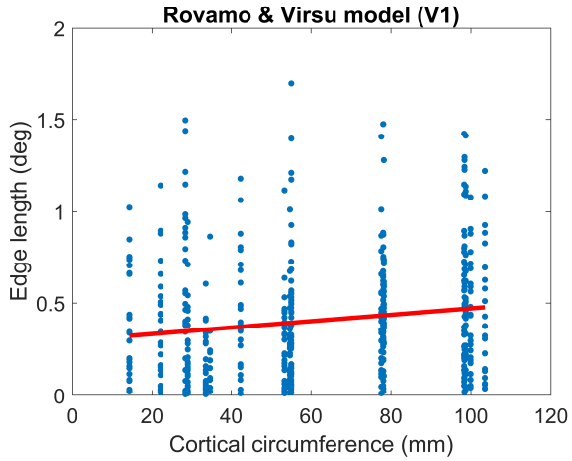
The M-scaling factors were borrowed from (Rovamo & Virsu,1979) and we plot edge length versus cortical length in Figure 12(a,b). This is a skeletal model with Rovamo and Virsu cortical magnification factors. The R^2 value explains how well the model explains the variability in the response based on the variability in the predictor values. The cortical length's R^2 reports higher value than the R^2 for the retinal length measurements.

From this regression model, we build an equation for the edge length as a function of the retinal circumference and as a function of the cortical circumference.

Harvey and Dumoulin in (Harvey & Dumoulin,2011), create a model that maps population receptive fields and cortical magnification factor as a function of the cortical magnification factor of the first field in the visual hierarchy, V1. Later fields such as V2,V3 and



(a)



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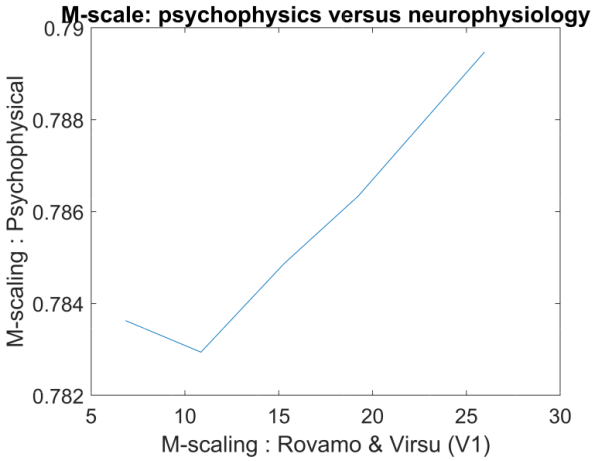


(c)

Figure 11: (a) Edge length versus retinal circumference r2: 0.04 (b) Edge length versus cortical circumference r2: 0.023 (c) A ratio of the M-scaling from experimental observer data and neuro-physiological study does not observe a flat slope indicating that animal studies and human data show a linear co-relation but are not equivalent.

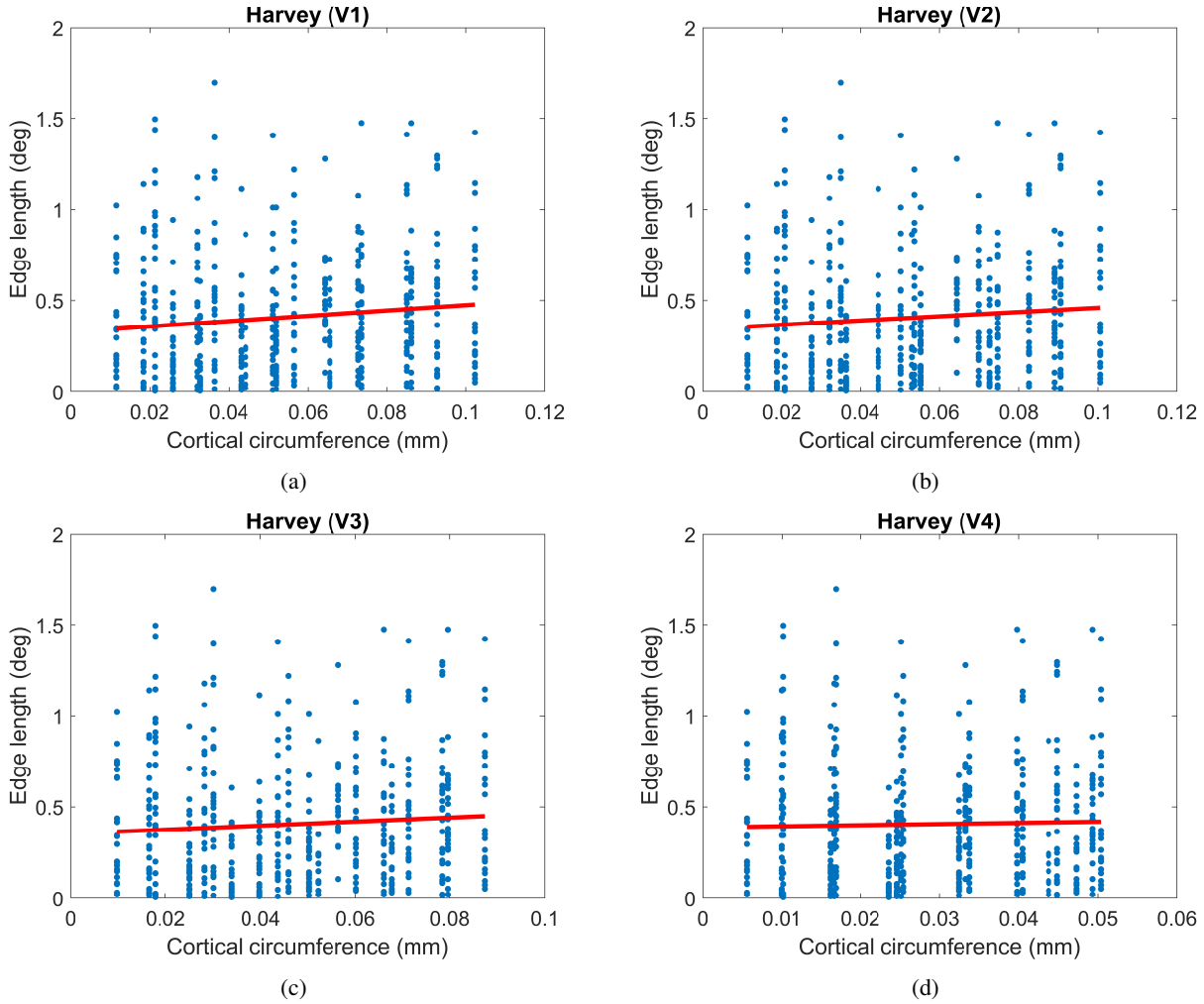


Figure 12: (a Retinal circumference versus edge length using the Harvey model V1 r2: 0.0135 (b) Retinal circumference versus edge length using the Harvey model V2 r2:0.0084 (c) Retinal circumference versus edge length using the Harvey model V3 r2:0.0057 (d) Retinal circumference versus edge length using the Harvey model V4 r2:0.0007.

Algorithm 1 Cortical mapping function

[1]
Computing the cortical length using the M-scaling magnification factor for a circle of a given radius and presented at a particular eccentricity.
radius:Radius of the circle

center: Center of the circle. The center, in cartesian coordinates, represents the eccentricity at which the circle is presented on the retinal 2D plane.

computeLengthOnCortex(radius,center)
Output: Cortical length (in mm) as represented on the cortex region called V1'

Initialization:
Set number of point samples on the circle, call it n
unit sample length = 1/n

Do:

Compute the tangent; t runs in unit sample length increments between 0 and 1
tangent = 2*π*radius*(-$\sin(2 * \pi * t), cos(2 * \pi * t)$)
speed = tangent

Cortical magnification factor for region V1. Rovamo's value used as an example
M= $25.19 * (eccentricity + 0.09)^{-1.53}$
Cspeed=M*speed

Compute the cortical length by multiplying the M-scaling magnification factor with the speed over the sample length.
len=Cspeed*unit sample length

model	loglikelihood	model equation
edgelength $\sim$1 + size + $(1\|user)$	13.6695	0.496 + 0.0394 * size
edgelength $\sim$1 + eccentricity + $(1\|user)$	-150.796	0.755 + 0.0135 * eccentricity
edgelength $\sim$1 + size + eccentricity + $(1\|user)$	27.80	0.433 + 0.04 * size + 0.0176 * eccentricity
edgelength $\sim$1 + eccentricity_min + $(1\|user)$	-127.2	0.683 + 0.038 * eccentricity_min
edgelength $\sim$1 + eccentricity_mean + $(1\|user)$	11.84	0.529 + 0.0568 * eccentricity_mean
edgelength $\sim$1 + size + eccentricity_mean + $(1\|user)$	24.49	0.498 + 0.0214 * size + 0.0286 * eccentricity_mean
edgelength $\sim$1 + size + eccentricity_min + $(1\|user)$	14.85	0.487 + 0.038 * size + 0.0062 * eccentricity_min

V4 must sample from V1. As evident from regression, a better summary of the relationship between the edge length seen during adaptation is provided by a cortical function than a retinal function. The cortical magnification factors used from lower level V1 (Rovamo and Virsu model) offers a better fit than the cortical magnification factors used from higher level V4 (Harvey model).

When subjects are reporting edge lengths, they are usually reporting a single edge length for the entire illusion but may not factor for peripheral influence. The peripheral factor could either be the minimum eccentricity since we know that foveal representations are stronger than flanking representations. The peripheral factor could also be characterized by an averaged mean eccentricity. This is the eccentricity that is formed as a function of the distance from fixation, integrated over the circle that is being presented.

We use the edge length that is initially reported by the user, and compare it as a function of retinal eccentricity, cortical eccentricity and peripheral eccentricity - both averaged mean and minimum representations. We show the interactions between the models that have only size, only eccentricity, mean and minimum eccentricity and size and eccentricity together with the user as a random effect.

From the table above, using loglikelihood, the model that best describes the response from users is size and eccentricity together. Size, as the sole fixed parameter, offers the best explanation to the edge length reported by the participants.

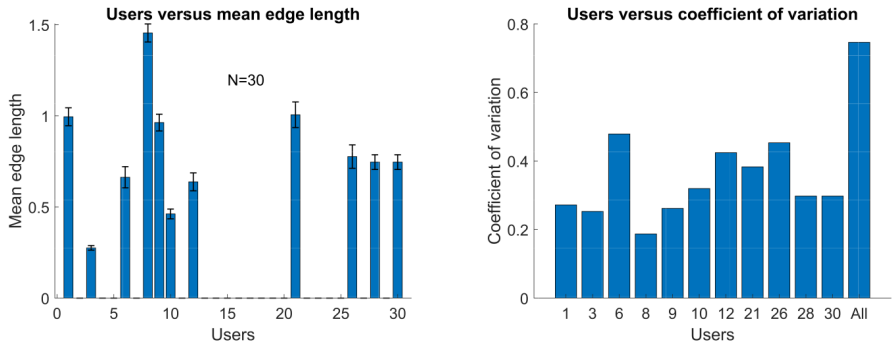
Do participants matter? What is the inter subject and intra subject variability with respect to edge length when considering all participants?

From Fig 13 (b), the users that report edge lengths (i.e. they see polygons instead of circles only) are reported as users 1-10. Over all stimulus conditions and all trials, as the coefficient of variation is much less than 1, the inter-subject variability is very low for users reporting edge lengths and thus, inter-subject values can be averaged as it does not carry wide subject-specific information. The 'All' bar, being less than 1, also shows that the inter-subject and intra-subject variability is relatively low.

A simple ratio of variance of the users versus the overall variance shows that the users individually do not contribute significantly to the mean. Below, we show the inter class coefficient (ICC) as a ratio of the overall variance and the variance of the users, which is a random effect.

$ICC = \sigma^2_{users}/(\sigma^2_{overall} + \sigma^2_{users})$

We find that most of the time, inter class coefficient, ICC, reported are much less than 0.5 indicating not much inter-reliability between the two variances. The users do not significantly influence the general mean reported for edge length. The various ICCs for the model designs are listed in the model table above.



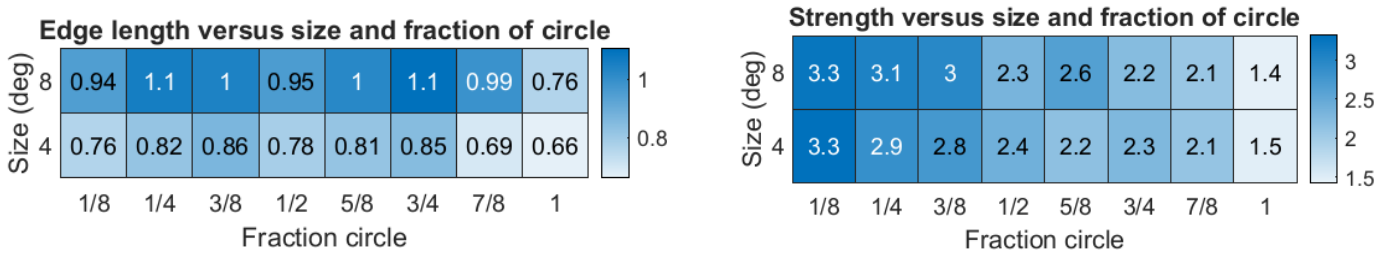
(a) (b)

Figure 13: Experiment: (a) Inter subject variability: Edge length is extracted from each subject. The bar for each subject encompasses all trials across all stimuli conditions. Some users report all circles. Their means are 0. (b) Coefficient of variation: The 'All' bar is calculated from all subjects and all repetitions. It reflects both inter-subject and intra-subject variability.

model	**ICC**	**Do participants influence the edge length mean?**
edgelength $\sim$1 + size + $(1\|user)$	0.0008256	No
edgelength $\sim$1 + eccentricity + $(1\|user)$	1.1057905	Yes
edgelength $\sim$1 + size + eccentricity + $(1\|user)$	0.151666 [Best Model]	No
edgelength $\sim$1 + eccentricity_min + $(1\|user)$	0.19844	No
edgelength $\sim$1 + eccentricity_mean + $(1\|user)$	0.941114	Yes
edgelength $\sim$1 + size + eccentricity_mean + $(1\|user)$	0.183109	No
edgelength $\sim$1 + size + eccentricity_min + $(1\|user)$	0.17636437	No

Results from Experiment 2

Participants did not report twice as large edge length with twice as large a stimulus. The edge length reported per arc length did not change greatly with arc length but changed with actual circle size. This demonstrates that sampling is based on the quality of the curve or curvature rather than the length of the curve. The strength reported was slightly lower for full circles compared to fractional arc lengths, alluding that the visual system has an affinity for closure and prefers to see shapes as composited closed circles where possible.



(a) (b)

Figure 14: (a) Mean edge length (in pixels) for different arc lengths 1/8 ,1/4 ,3/8 ,1/2 , 5/8, 3/4 and 1 of the circle, circle of deg 4 and 8. (b) Strength reported for different arc lengths 1/8 ,1/4 ,3/8 ,1/2 , 5/8, 3/4 and 1 of the circle, circle of deg 4 and 8. Strength was marked on a scale of 1-10 for polygonal percepts. Lowest strength was reported for full circles.

Discussions

We show that size and eccentricity together predict the edge length seen during in-place adaptation. Participants in general do not influence a change in the edge length reported for this model. Edge length increases with stimulus size and eccentricity. Mean and minimum eccentricity components of a stimuli's feature have a less pronounced effect on the edge length seen during adaptation. Size has a more pronounced effect on the edge length seen while eccentricity has a more modest effect. From the experiments of Sakurai et. al (Sakurai & Beaudot,2015;Sakurai,2014), we already know that the production of polygons is a cortical process. We show that Rovamo and Virsu's model (Rovamo & Virsu,1979) for approximating M-scaling, the equation that projects point images on the retinal visual field onto the early visual cortex region, V1, and provides the best neuro-physiological model that equates the retinal behavioural edge lengths seen during in-place adaptation with its cortical mapping. The results also support the theory that there is a loss of 'shape' in peripheral vision by the reduced number of participants reporting the presence of edge lengths preferring instead to report purely circular shape.

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