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ORIGINAL ARTICLE

Normal Aging and the Perception of Curvature Shapes

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ABSTRACT

Purpose. The present study assessed whether different curve geometries involve different perceptual processing levels and whether these perceptual requirements can interact with the normal aging process.

Methods. Amplitude thresholds for three different curve types were assessed for young and older observers using 2AFC psychophysical methods. The stimuli were individually adjusted for visibility. The three stimulus types evaluated represented a bell shape, a quadratic, and a compressed arc function.

Results. As predicted, the geometry influenced the perception of curvature where the compressed arc was most difficult to perceive followed by the quadratic and bell-shaped curves. Moreover, older observers showed relatively higher thresholds for the quadratic and compressed arc shapes, while they had similar thresholds to the younger observers for the bell-shaped function.

Conclusions. In general, the data support the notion that aging affects the processing of curvature requiring the integration of oriented receptors. This is in accordance with studies that have found reduced orientation selectivity of cortical neurons in senescent animals. Our findings suggest that older observers would have more difficulties with form discrimination tasks where curvature is an inherent component of the image and also predict age-related differences in perceiving ophthalmic lens-induced distortions.

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Key Words: aging, curvature, distortion, shape, faces

Normal aging is accompanied by presbyopia; a loss of ability to focus at near distances. Presbyopic symptoms appear in the early 40s and increase progressively for several decades. Although there are different approaches for correcting presbyopia, the simplest and most common method remains ophthalmic lenses. Any ophthalmic lens induces distortions, which can be simply defined here as a straight line that is seen as curved when the light rays travel through the lens.[1] A particular case of visual distortion is present when progressive lenses are used because the distortions are asymmetrical with generally more curvature generated in the lower visual field.[2] To get a grasp of the impact of such distortions, it is imperative to understand how observers perceive curvature shapes and, in particular, how the perceptual changes that accompany normal aging interact with this ability. In the present study, we address two questions: are different curvature shapes processed at different levels of ability as predicted by different curvature models?[3,4] If so, how does this interact with normal aging processes? Wilson[5] and Wilson and Richards[4] suggest that curvature perception is predicted by orientation-selective visual mechanisms; Leventhal et al.[6] found that both orientation and direction selectivity of cortical cells decrease with age suggesting an age-related decline in perceptual performance. It follows from these arguments that an age-related decline in curvature perception should be observed at various levels depending on curvature shape.

Curvature Perception

An efficient perception of objects and spatial structure requires a good evaluation of curvature. It has been shown that human ability to perceive curvatures is essential for object discrimination.[7] Several models have been established to explain curvature perception.[3–5,8–10] For example, Koenderink and Richards[3] suggest a model of curvature discrimination mechanisms represented by 2 $\times$ 3 matrices of inhibitory and excitatory units. The model measures the ratio of excitatory and inhibitory units and produces a response depending on the curvature and the width of the contour. Another model proposed by Wilson[5] and Wilson and Richards[4] suggests that curvature perception is predicted by orientation-selective visual mechanisms. They suggest that high-amplitude curvatures are evaluated by high spatial-frequency mechanisms located at the point of maximum curvature. The receptors would evaluate the curvature according to the extreme point of the curvature. Furthermore, for low-amplitude (<2deg) curvature, the system compares the response of two orientation-selective high spatial frequency units located at a fixed distance from a central unit located in the midpoint (maximum) of the curvature.

In addition, the "shape" of the curve may influence the way it is processed. The curvature shape refers to a difference in trajectory and angle along the curvature (Fig. 1). In relation to current models, curvature information can be processed by a series of adjacent oriented filters, as defined by the association field theory.[11–13] In such an approach, efficacy of processing has been defined in terms of the relationship (parameters) of local Gabor patches making up the field defining the curve (i.e., distance, contrast, orientation, spatial frequency, etc.). For example, good performance is obtained when there are little or smooth changes in the direction of the trajectory (<60° difference between two elements) defined by Gabor patches and decreased performance is associated with rapid changes and abrupt angles in the trajectory (>60° difference between two elements). Therefore, curved stimuli displaying different trajectories could result in different processing requirements. Legault et al.[14] showed that observers had no differences in thresholds between periodic line stimuli of various contour frequencies (also defined as a hyperacuity task, number of oscillations in a line stimulus[15,16]). They also showed that sensitivity peaked at one cycle per image, i.e., sensitivity did not improve with increasing number of cycles. For this reason, the present study focused on the effect of shape on non periodic curvatures.

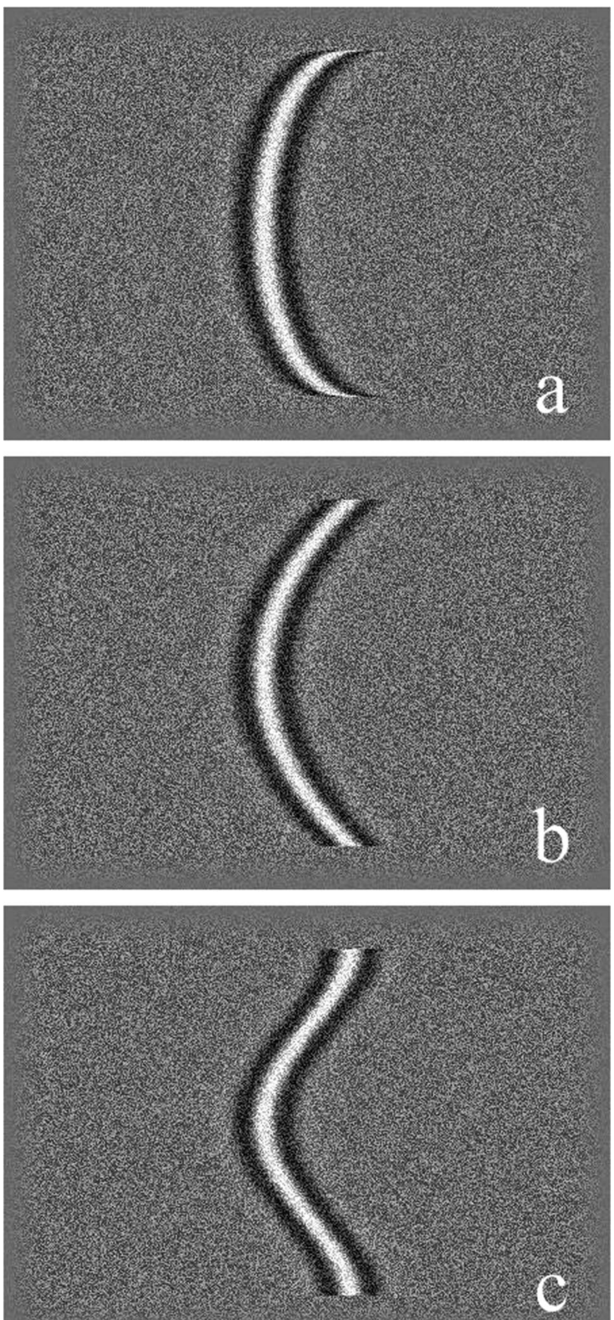

FIGURE 1.
Stimuli used in our experiments: (a) represents compressed arc curve, (b) quadratic curve, and (c) bell-shaped curve.

Aging and Visual Perception

Some visual functions are known to decrease during normal aging. Older adults show decreased performance for visual acuity, contrast and color sensitivity, motion perception, symmetry perception and binocular vision, etc.[17–21] However, older adults can also perform as well as younger observers on different tasks such as hyperacuity discrimination tasks.[22] Very few studies have evaluated tasks involving the impact of aging on the perception of curvature. A recent study on the effect of aging on contour discrimination by Wang[23] compared the effect of normal aging on the detection of the deformation of both circular and linear contours and found that no difference occurs with age at low modulation frequencies, but a significant difference emerged at higher modulation frequencies.

Recent experiments on aging monkeys have shown that visual neurons of older monkeys respond less efficiently to stimuli orientation and direction than those of younger monkeys.[24] Also, Leventhal et al. found an age-related reduction of cortical selectivity and inhibition resulting in an increased response to all stimulus orientations. After an injection of an inhibitory neurotransmitter (GABA) agonist, old monkeys performed like young monkeys. The authors suggest that the reduction of GABAergic inhibition occurs with aging and decreases the orientation and direction selectivity, thereby decreasing the inhibition selectivity to all orientations.[6,24] Similar experiments on cats have replicated these results.[25] A natural extension of this is that human older observers should also have a decrease in orientation and direction selectivity. A recent behavioral study lends support to this hypothesis; Betts et al.[26] found that older adults required briefer stimuli durations than the younger group to extract information from a task where lateral inhibition is assumed to play an important role. They proposed that older adults demonstrated better performance on their task because, like older monkeys, they have less inhibition and have higher spontaneous firing rate to nonpreferred orientations.

If older adults are less selective to various orientations, it follows that, in a curvature detection task that implicates orientation detectors, older observers would show higher thresholds. One should observe an age-related effect on curvature perception because it is assumed that curvature mechanisms solicit oriented receptors[4,5] and there should also be an age by shape interaction given that the oriented receptors involved are different for the different shapes.

In summary, the two main purposes of the present study were 1) established if the shape (geometry within a cycle) influences curvature perception in young adults and 2) determine if aging interacts with the ability to process different curvature shapes.

Experiment 1

The purpose of the first experiment was to establish if curve shape influences its detection, an important step prior to testing older observers in order to evaluate the orientation selectivity vs. aging hypothesis for curvature perception. Presumably, different detection thresholds should occur if there is a more abrupt change in the curvature trajectory[11–13] but the question remains whether this pattern of results obtained with Gabor patches transfers to full line stimuli.[27] For this experiment, the effect of "geometry" was measured for luminance-defined curves using three different geometric profiles that were arbitrarily defined by manipulating a single variable in the formula for a quadratic curve. The shapes generated were either bell shaped, quadratic, or a compressed arc (see formula and images).

Methods

Observers. An author (I.L.) and nine subjects naïve to the purpose of the experiment participated in this experiment. The age range was between 24 and 28 years. All had normal or corrected-to-normal vision.

Hardware & Stimuli

Apparatus. Stimuli were presented on a 21-in Dell P1130 monitor with a refresh rate of 60 Hz. An AMD Athlon 1 GHz computer combined with an Aopen Mx200 graphics card was used to compute and display the stimuli. The monitor luminance intensity was calibrated using a photometer. The mean luminance of the display was 29 cd/m^2. Gamma-correction was verified on a regular basis to ensure precise calibration.

One of the most basic curve shapes is a quadratic curve. To allow a direct comparison between the perception of a quadratic shape and a full single cosine cycle generated from a periodic line stimulus that we used previously,[14] we generated a formula that could make the shape vary from a quadratic (Fig. 1b) to a shape similar to a single cosine (bell shape, Fig. 1c), to a compressed arc (Fig. 1a). The shapes were defined by the following formula:

$$D(y) = a * \left[\left(1 - \left(\frac{y}{h} \right)^2 \right)^f - 0.5 \right] + j \qquad (1)$$

where a represents the amplitude of the curvature, that is the distance on the x axis between the extremity and the center of the curvature. In the present experiment, a was the dependant variable, h (height) represented the distance between one extremity and the center of the curvature on the y axis, which was fixed to 2° of visual angle (dva), j represented a jitter on the x axis introduced to avoid positional cues and varied randomly between −0.25 and 0.25 dva, f modulated the shape of the curvature. In our case, f had 3 values, 0.5 (compressed arc), 1 (quadratic), and 2 (bell shaped).

The stimuli were luminance-defined:

$$L_{LM}(x,y) = L_0(1 + M(x,y) + N(x,y)) \qquad (2)$$

where $M(x,y)$ and $N(x,y)$ represent the modulation profile and noise function, respectively, and L0 is the mean luminance background. Uniform noise was used where the difference between the maximum and the minimum was 50% ($-0.5 < N(x,y) < 0.5$) of the maximum luminance. Each noise element was static and corresponded to 1 pixel. Background noise was used here only to allow direct comparison with our previous experiment contrasting luminance vs. contrast-defined stimuli.[14]

The modulation profile was the fourth normalized Gaussian derivative:

$$M(x,y) = c\left[1 - \frac{(x - D(y))^2}{\sigma^2} + \frac{(x - D(y))^4}{12 * \sigma^4}\right] * \exp\left[\frac{-(x - D(y))^2}{2\sigma^2}\right] \qquad (3)$$

where σ is the standard deviation (controlling the width of the line), which was fixed to 0.25 dva, c is the modulation contrast which was adjusted for each subject, and $D(y)$ represents the shape of the vertical curve defined as the distance from the median vertical line for each point of the curve (Equation 1).

At the viewing distance of 114 cm each pixel was 1/64 × 1/64 dva, the stimulus length was 4 dva with a width of 0.25 dva.

Procedure

A two-alternative–temporal-forced-choice procedure combined with the method of constant stimuli was used to measure contrast and amplitude detection thresholds. The first experiment was performed to perceptually equate for individual differences in sensory input. A contrast detection threshold was obtained in which the observer had to identify the interval containing the straight line in noise, from a second interval containing only noise ($c = 0$). The straight line interval had a contrast (c) higher than 0 and an amplitude (a) equal to 0. A block of testing (one session) was composed of 210 trials: seven contrast levels presented 40 times in a pseudo random manner. A Weibull function[28] was used to determined the lowest contrast level to correctly detect the stimulus 99.9% of the time.

The second task consisted in determining curvature amplitude thresholds. First, the contrast of the stimuli was fixed independently for each subject based on the previous task. Once the intensity of the stimuli was perceptually equated, the task consisted in identifying the interval containing the curvature ($a > 0$) vs. a second interval containing a straight line ($a = 0$). A block of testing (one session) was composed of 30 trials of one type of curvature with seven amplitude levels presented in a pseudo random manner. A Weibull function[28] was used to determine the curvature amplitude (a) threshold defined with a 75% correct criterion. The f had one of three values (0.5, 1, and 2) depending on the type of curvature tested and the contrast (c) was specific for each subject.

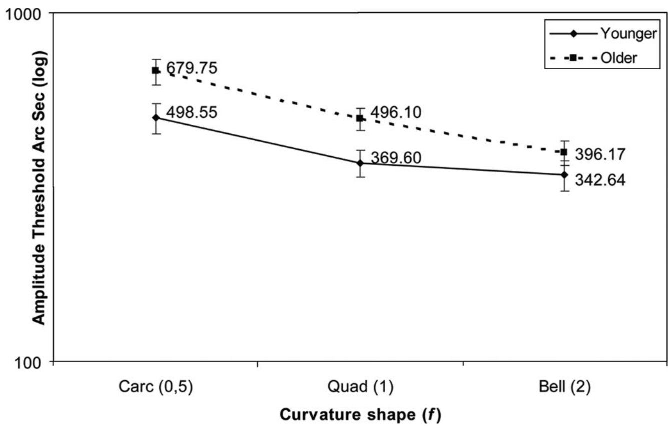

FIGURE 2.
Curvature detection as a function of curve shape for younger and older observer.

Results and Discussion

Results revealed that observers obtained higher detection thresholds on the compressed arc compared with the quadratic and bell shapes. All observers obtained a similar negative slope. A 1-factor analysis of variance (ANOVA) was used to analyze amplitude threshold differences on the average group data (Fig. 2, solid line). A main effect of curve was observed, $F(2,27) = 4.490$, $p < 0.05$. A significant effect was found for the compressed arc curve when compared with the quadratic and bell curve shapes, $t(1,9) = 5.250$, $p < 0.01$; and $t(1,9) = 6.037$, $p < 0.01$, respectively. However, detection thresholds for quadratic and bell shapes did not differ, $t(1,9) = 1.452$, $p = 0.180$. We conclude that the compressed arc stimulus is the most difficult to process. This is possibly caused by the fact that this particular shape is defined by more abrupt angles in condensed areas as opposed to the other shapes, which is consistent with the curvature models discussed above.

Experiment 2

Given that curve shape influences observers' discrimination thresholds, we can test the second hypothesis that curvatures generating higher thresholds in young normal observers (presumably because of higher or different oriented pooling requirements) should be more affected by normal aging.[17] Furthermore, this experiment addresses the question under which the pooling of oriented receptors involved in curvature perception would be affected by normal aging, which would be consistent with the aging monkey studies cited above.[6,24]

Methods

Observers. Twelve older observers (mean age 68.8 ± 3.04 years, range, 64–74 years old) naïve to the purpose of the experiment participated in this experiment. Ten subjects in our older group had a corrected visual acuity of 20/20 and two had 20/25. A pair of 0.87 diopter lenses was added to their habitual refractive correction to compensate for accommodation at the testing distance of 114 cm. Testing was binocular, except for one old amblyopic subject who nevertheless showed similar results to other participants. Older observers completed the Mini-Mental State Exam, a screening measure for cognitive impairment. All subjects' scores were within the normal range (range, 26–30/30; subject mean was 29.6/30).[29] Furthermore, the majority of our older subjects had university level education; all were highly autonomous and came to our laboratory on their own. Therefore, they were all considered cognitively healthy.

Apparatus & Stimuli

For experiment 2, the same setup, stimuli and procedure as experiment 1 were used.

RESULTS

Older adult were compared with our younger group from experiment 1. A 2 × 3 split-plot ANOVA; age (between variable) × curvature (within variable) revealed a significant age × curvature interaction, $F(1,20) = 5.689$, $p = 0.027$ (Fig. 2). No significant difference was found between groups of observers for the bell-shaped curve ($t^{1,20} = 1.149$, $p = 0.26$). However, the significant age by curvature shape interaction comes from the group differences in the other two shapes (Compressed arc: $t(1,20) = 2.417$, $p < 0.02$; Quadratic: $t(1,20) = 2.581$, $p < 0.01$). Older observers' detection thresholds increased by 25% relative to the younger group for the nonbell-shaped curves. This is not a consequence of contrast thresholds as they were equivalent between the older and younger observers (young = 0.060, SD = 0.016; older = 0.053, SD = 0.011).

Control Experiment

One could possibly argue that the age by curvature type interaction obtained above may be due to an interaction between the type of curve and age-related differences in contrast sensitivity. To address this potential confound, we conducted an additional control experiment with five young (mean age = 26.8) and five older (mean age = 67.0) observers. We tested their contrast sensitivity to the three types of curves with preset amplitudes that were two times the mean threshold for each curve type obtained in experiment 1 and compared that with the original line condition used to establish individual contrast thresholds in the above experiments. If there is a specific aspect of the curve shape that interacts with contrast sensitivity and aging, we should obtain differences in contrast sensitivity as a function of curve type and age. As expected, we found identical contrast thresholds for each group and each stimulus type. These results are reported in Table 1. A repeated measure ANOVA shows that F ratios were all below 1 with no significant differences for any condition.

DISCUSSION

Our results are consistent with the two hypotheses initially projected. First, curvature shape makes a difference and curvature shapes are not all processed the same way by the visual system. This is supported by the data showing that the compressed arc curve requires greater amplitude differences. The data also show that older observers have more difficulty processing the compressed arc and quadratic curves demonstrating that there is something inher-

TABLE 1.
Contrast thresholds and standard deviation (SD) for the four types of targets (compressed arc curve, quadratic curve, bell shape curve, and line)

	Younger		Older	
Stimuli	Mean	SD	Mean	SD
Compressed arc	0.0304	0.0056	0.0310	0.0018
Quadratic	0.0247	0.0048	0.0307	0.0048
Bell	0.0300	0.0046	0.0290	0.0067
Line	0.0251	0.0095	0.0274	0.0038

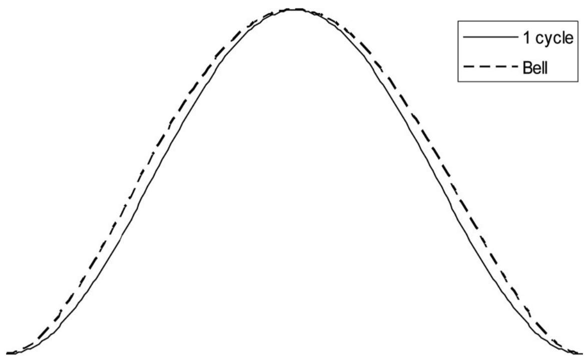

FIGURE 3.
Contour frequency of one cycle vs. bell-shaped curve.

ently different between these curves and the bell-shaped curve. In general, these data are consistent with the proposition that the pooling of oriented receptors may be affected in aging and that oriented pooling may be more important for processing quadratic and compressed arc shapes than the bell-shaped curvature pattern.

Our results are generally consistent with the different curvature models proposed in the literature. The model of curvature perception proposed by Koenderink and van Doorn[30] suggests inhibitory and excitatory units arranged in a 2 × 3 matrix structure. When applying this model to our curves, the compressed arc image generates more inhibition, therefore, a smaller response compared with the quadratic and bell shapes that stimulate primarily the excitatory zones. Moreover, because the curvature is concentrated in the curve extremity, the model proposed by Wilson and Richards[4] predicts that receptors along the curve will have higher distances between each other for the compressed arc shape requiring more pooling energy and inducing higher thresholds. Furthermore, as proposed by Hess and coworkers,[11–13,31] successive elements in a visual pattern are harder to perceive when abrupt changes or abrupt angles occur between elements, suggesting that the relatively steep changes in the compressed arc trajectory could account for the increased thresholds as, at the curvature thresholds, none of the changes in the curves are steep in absolute terms.

Previous studies have demonstrated that Vernier and similar spatial discrimination tasks are unaffected by age.[22,32–34] It is possible therefore that our bell-shaped stimuli and the one cycle periodic line stimuli (used in a previous study) are processed in a similar way as Vernier type tasks. However, thresholds obtained for our curves are higher than what is expected in classical hyperacuity tasks. This may reflect that our curves were tested in noise and implied a certain distance between the anchorage points (extremities) and the central portion of the curve (larger gap). It is known that noise, gap size, and contrast influence hyperacuity tasks.[32,35] Furthermore, in a previous study we showed that periodic line stimuli containing one or eight cycles of distortion generated very similar results.[14] We found that whether the stimuli were luminance or contrast defined, the observers' performance remained identical when the stimuli were matched for visibility. The bell-shaped curve used here showing no significant effect of aging, as Fig. 2 shows a (nonsignificant) effect of age for the bell-shaped curve, was almost identical to the line containing one cycle of distortion in our previous experiment[14] (Fig. 3). Furthermore, Wang[23] showed no difference of performance between young and older adults when using low radial frequency patterns similar to our periodic line stimuli with one cycle of distortion (therefore similar to the bell shape).

Leventhal et al. suggested that higher mammals with well-developed visual systems should show a reduction in selectivity to orientation and direction with aging.[6,24] If the perception of our curves requires the integration of different oriented receptors, the Leventhal proposition can account for our data. Our results support the idea that higher mammals with developed visual systems show a reduction of orientation selectivity with aging. Moreover, the results for compressed-arc and quadratic curve shapes are consistent with results found by Betts et al.[26] that stated that older adults demonstrated better performance on their task because, like older monkeys, they have less inhibition and have higher spontaneous firing rate to various orientations. Their results suggest a reduction of inhibition and an increase of spontaneous firing in older adults in orientation selective cells.

The differential results obtained for our older observers in regards to curvature shape cannot be accounted for by and age-energy interaction. First, the spatial frequency of the line used was in a range that is generally unaffected by aging. Second, we assessed individual contrast sensitivity of the observers because we wanted to compare first- and second-order functions with equal visibility in another study.[14] It turns out that the mean contrast thresholds for the stimuli used here (first order) were equivalent between the older and younger observers. So it is unlikely that our results can be attributed to contrast or energy differences in the stimuli and their interaction with aging.

The age-related threshold increase for the compressed-arc and quadratic curve shapes supports the notion that these shapes imply orientation integration. It has been demonstrated that age-related deficits are increasingly obvious when the processing requirements of visual information increases.[17] Because a significant age-by-curvature interaction was shown where some shapes generate higher thresholds, and where the most difficult curvatures to perceive for the young normal observers become even more difficult to perceive for the older observers, it is possible therefore that this effect is because of increased processing demands. Furthermore, those results may help to understand the age-related deficits observed in face perception experiments.[36] Faces are composed of a variety of curve shapes among other things. The higher curvature perception thresholds for some shapes observed in older observers may be the source of the age-related changes in face perception as compared with other objects such as chairs or houses that are mainly composed of straight lines and perpendicular angles presumably less affected by normal aging.

Many methods for correcting age-related presbyopia (loss of ability to focus at near distances) induce visual distortions in the form of curvature.[2] It is important, therefore, to understand how well older observers can perceive curvature. This may lead to a better understanding of when observers will or will not be bothered by optically induced visual distortions, which could subsequently influence ophthalmic lens design.

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