Explanation of the Perceptual Oblique Effect Based on the Fidelity of Oculomotor Control During Saccades

Khuong N. Nguyen*, Xi Liu†, Oleg Komogortsev‡, Ricardo Gutierrez-Osuna*, and Yoonsuck Choe*
*Department of Computer Science and Engineering, Texas A&M University - College Station, TX 77843
†Department of Electrical and Computer Engineering, Texas A&M University - College Station, TX 77843
‡Department of Computer Science, Texas State University - San Marcos, TX 78666

***Abstract*—The oblique effect, observed in both humans and animals, refers to the phenomenon of differential perceptual performance in visual recognition tasks that involve horizontal and vertical, vs. diagonal patterns. Furthermore, differences have been found in the visual cortical organization for the horizontal and vertical vs. diagonal representations. However, why such structural differences leading to functional divergence emerge in the first place is yet to be explained. In this paper, we propose a potential explanation for the oblique effect based on the differences in the sampling of oriented edge inputs along different angles due to mechanics of eye movement. Our hypothesis is that the oblique effect is mainly due to eye movement along the diagonal directions being less precise than the horizontal and the vertical, which causes the sampling of the angles more variable for the diagonal orientations. This will, in turn, lead to structural changes in the visual cortex, which is known to be sensitive to the natural stimulus statistics. We used our Two-Dimensional Linear Homeomorphic Oculomotor Plant Model to simulate saccadic eye movements and sample visual inputs along the eye movement trajectories. Then, we used a multilayer perceptron (as a simple surrogate of the visual cortex) to test how easy it is to learn to classify the different angles from these samples. We found that our results are consistent with the oblique effect data reported in the experimental literature, thus supporting our hypothesis. We expect our work to shed new light on the role of the motor system in determining perceptual organization and function.**

I. Introduction

The oblique effect refers to the phenomenon in which perceptual performance in visual tasks are lower for obliquely (diagonally) oriented patterns, compared to those that involve horizontally or vertically oriented patterns [1]. Ernst Mach first discovered the effect in 1861, while conducting a visual experiment in an attempt to measure human perceptual performance [2]. Research in neuroscience literature confirms that the effect is also present in several animal species [3], [4].

Despite the multiple reports in the literature confirming the oblique effect's existence, its underlying cause remains unexplained. Most studies agree that the oblique effect happens in the visual cortex but fail to elaborate on its fundamental origin [5], [6]. Li et al. [1] suggested that the oblique effect is due to intracortical mechanisms, whereas Furmanski et al. [7] found that in the human visual cortex, horizontal and vertical stimuli cause higher neural responses than obliquely oriented stimuli. Further investigations indicate that this phenomenon is due to the selectivity of horizontal and vertical orientations in the parahippocampal cortex, which is in charge of scene perception in the brain [8]. We propose that a possible explanation can be found in the oculomotor system. Research in active vision and perceptual performance discovered that saccadic eye movements (SEMs) follow different systematic curvatures for different angles [9]. While horizontally and vertically SEMs are smooth and aligned along the major axis, oblique SEMs experiences shakiness and deviation from the center lines. Given the above, we propose that the oblique effect is due to less precise ocular motions along the oblique directions, which makes the image samples taken along the trajectory more variable than the samples taken along the vertical or horizontal directions.

In this paper, we ran computational simulations of the visuomotor system to test our hypothesis. We used our Two-dimensional Oculomotor Plant Mathematical Model (2D-OPMM, Fig. 1-2) [10] to simulate eye movements for input sampling, and model orientation perception based on these samples using a standard classifier (a multilayer perceptron). Note that the specific choice of the classifier is not necessary since we are interested in the learnability of the angles based on the samples. Our results show that the angles of the different oriented edges sampled based on 2D-OPMM eye movement trajectories are harder to classify for the diagonal orientations than the horizontal or vertical orientations, providing support to our hypothesis.

The rest of this paper is organized as follows: Section II provides background on the oblique effect and active vision research. Section III briefly introduces 2D-OPMM and how we reproduce the oblique effect. Section IV presents the experiments and results. Sections V and VI discuss our findings.

II. Background

A. The Oblique Effect

The history of the oblique effect began when Ernst Mach discovered a deficiency in perceptual performance during one of his human subject studies in 1861 [2]. In this study, he asked human participants to recognize two adjoining parallel lines, some of them have orientation angles greater than 0 degrees. The experiment showed that the observers' errors were lowest for horizontal and vertical orientations and highest for the 45-degree orientation.

It was not until 1972 that this phenomenon was given its current name by Appelle [11]. In his review, he confirmed the effect appears not only in humans (both adults and children) but also in several other species where perception and discrimination performance vary with different orientations of the stimulus. Appelle also suggested the effect is a function of the number of cells in the visual cortex that are in charge of analyzing orientation stimulus. Further investigations uncovered two major categories of oblique effect. The first category, commonly known as the class-1 oblique effect, involves visual tasks directly engaging the basic function of the visual system such as perceptual acuity. The second category (class-2 oblique effect) involves tasks that reflect learning, cognitive process, and memory [12].

Attempts to explain the origin of the oblique effect have pursued two major directions: physiological and empirical. The empirical direction aims to explain the oblique effect by finding a "purpose" for it, i.e., is the oblique effect a random event or the consequence of natural selection to adapt to the environment [13]. However, empirical explanations failed to uncover the underlying mechanism of the oblique effect. Thus, explanations based on those results cannot be used to reproduce the oblique effect on mechanistic grounds. In contrast, the physiological explanations focus on the question: Which step in visual processing contributes most to the oblique effect? Differences regarding orientations can emerge at three stages within the visual pathway: (1) Eyes captures the image of the objects via eye movements and project the images on the retina. (2) The neural pathway that connects the retina and the visual cortex transmits the projected images as nerve signals. (3) The Visual cortex processes and analyzes the received signals. Hubel and Wiesel [14] investigated neural processing of orientations and the distribution of preferred orientation of the visual cortical neurons. They found fewer neurons were representing the oblique direction than the vertical and the horizontal. Additionally, work by Coppol on ferrets showed on average, 7% more of the animal's visual cortex was favorably activated by vertical and horizontal contours compared to oblique contours [15]. A study by Chapman [16] in the same year also agreed with the above but did not explain why this kind of bias came about.

How do these stimulus-specific differences arise in the visual cortex? Computational models of cortical development can potentially help answer this question. Visual cortical development models have been used successfully to model orientation preferences, tilt aftereffects, binding and segmentation, and contour integration [17]–[19]. These models have shown the complex structural organization and function of the visual cortex are mainly due to an input-driven self-organizing process. Additional studies [17] (chapter 13) have revealed that the visual cortical development process exhibits stimulus-specific differences in structure and function when the learning algorithm is subjected to differential natural stimulus statistics during development. According to these studies, differences in stimulus presentation frequency and input feature (curvature) distribution could result in differentiation in both the structure (lateral connection profiles) and the function (contour integration performance). These results lead us to hypothesize that

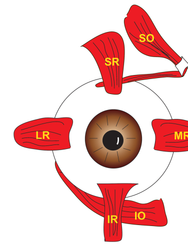


Fig. 1: **The extraocular muscles that control the ocular motor system [20].** LR is the Lateral Rectus. MR is the Medial Rectus. SR is the Superior Rectus. IR is the Inferior Rectus. SO is the Superior Oblique. IO is the Inferior Oblique.

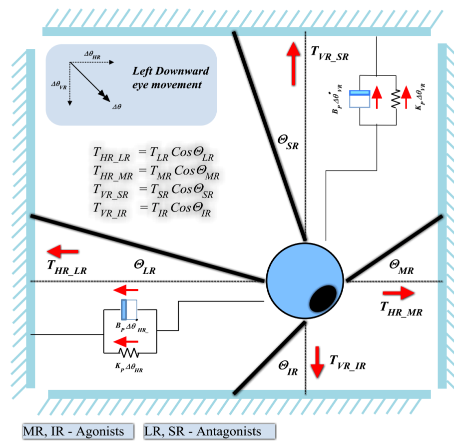


Fig. 2: **2D-OPMM: front view.** Left downward saccadic eye movement driven by medial rectus and inferior rectus as agonists, and lateral rectus and superior rectus as antagonists. See text for details [21]–[23].

input sampling if biased by the variability of the trajectory of eye movement along the major axis, will lead to the differential structural organization and functional performance.

B. The Oculomotor System

In humans, eye motion is controlled by a set of muscles known as the extraocular muscles. There are six muscles in total, including the superior rectus, inferior rectus, lateral rectus, medial rectus, superior oblique and inferior oblique (see fig. 1). Horizontal movements of the eye are driven by the medial and lateral rectus, whereas vertical movements are driven by the superior and inferior rectus. Diagonal movements are driven by a combination of forces exerted by superior or inferior rectus and, lateral or medial rectus. Finally, the superior and inferior obliques are in charge of rolling the eyeballs.

Eye movements are of four primary types: saccades, pursuit, vergence, and vestibular-ocular [24]. In this study, we are interested only in saccadic eye movements (SEMs), which are rapid movements of the eyes that suddenly shift the fixation point. It has been shown that SEMs between two different gaze positions result in curved and tortuous trajectories [25]. Viviani et al. [9] have shown these saccades are not straight lines and

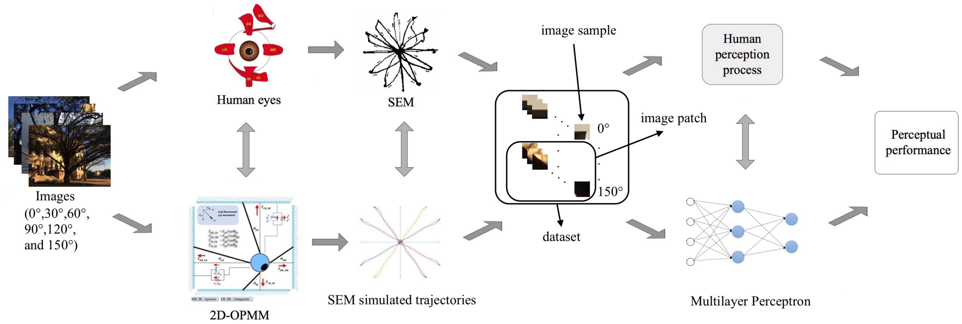


Fig. 3: **Overview of the experimental procedure.** 2D-OPMM is used to generate SEM trajectories. Using these trajectories, images patches are generated from the images which are later fed into the multilayer perceptron to train and test. The corresponding human visual process is shown above (vertical arrows simply show the correspondence).

follow different systematic curvatures as shown in Fig. 4b. The evidence in [9] also indicates while horizontal and vertical SEMs are smooth and steady, oblique SEMs experiences shakiness and deviation from the center line. This variability can be explained based on the muscles that control the type of movements as mentioned earlier. Each vertical or horizontal SEM is driven by just a pair of opposing muscles (lateral + medial rectus for horizontal and superior + inferior rectus). By contrast, four muscles (lateral, medial, superior, and inferior) are required to perform oblique SEMs. We hypothesize that the motor performance variation corresponding to different types of SEM is the major cause of the perceptual oblique effect, and this is explained in detail in section III.

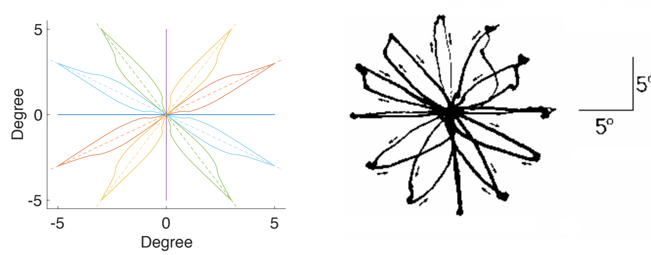
III. Methods

This section introduces the Two-Dimensional Linear Homeomorphic Oculomotor Plant Mathematical Model for oriented input sampling and the orientation classification method used to test our hypothesis.

A. Two-dimensional Oculomotor Plant Mathematical Model

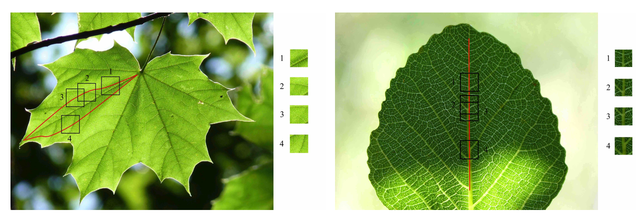
To generate SEM trajectories, we used our Two-dimensional Oculomotor Plant Mathematical Model (2D-OPMM) [10]. This model was designed specifically to simulates saccadic eye movements by modelling the muscles that control the eye movement, the agonist (AG) muscles that pull the eye to the desired direction and the antagonist (ANT) muscles that oppose the pull [1]. A saccade is described by two components: horizontal and vertical. The mathematical description of a saccade is $\dot{x} = Ax + u$ & $\dot{y} = Bx + c$, where A and B are transition matrices, x (represent horizontal component) and y (represent vertical component) are state vectors, and u and c are control vectors for the horizontal and vertical components. A detailed description of the model can be found in [21]–[23]. Fig. 2 shows a left downward saccadic eye movement example generated by the 2D-OPMM.

[1]Note that four major muscles control the movement of the eye: lateral rectus (close to the ear - LR), medial rectus (close to the nose - MR), superior rectus (top - SR), and inferior rectus (bottom - IR). We did not include the two oblique muscles for simplicity as they control eye roll.



(a) Simulated SEM trajectories (b) Real SEM trajectories

Fig. 4: **Saccadic eye movement trajectories with a max degree of 5°.** (a) shows saccadic eye movement trajectories (0°, 30°, 60°, 90°, 120°, and 150°) generated from the 2D-OPMM. The broken lines are center lines. (b) shows the human saccadic eye movement trajectories [9].



(a) 30° (b) 90°

Fig. 5: **Generating 30° and 90° image samples (max amplitude = 5°) from the corresponding saccadic eye movement trajectories.** (a) shows 4 image samples from the trajectory along the 30° saccade. (b) shows 4 image samples from the 90° trajectory. The trajectories are plotted in red and each black square represents an image patch sample. Each image patch was 225×225 pixel in size and the size of the natural image was 3264×2448 pixel.

B. Learnability of Visual Orientation Perception

Using image patches sampled along the saccade trajectory for each orientation, we tested how easy it is to learn the mapping from these sampled image to the orientation (angle) using off-the-shelf classification algorithms (note again that the specific classification algorithm used is not important since we are more interested in the learnability of the sampled inputs). This technique circumvents the complex processing in the visual cortex and instead focuses on the nature of the information made available to the visual cortex by the motor system. We used image samples themselves as the input after binarization, bypassing the retinal and lateral geniculate nucleus processing, directly feeding them into a multilayer perceptron with one hidden layer (8 hidden neurons) trained with backpropagation [26] as a surrogate for visual cortical orientation perception.

IV. Experiments and Results

We carried out the experiment in a processing pipeline where a series of steps were used including generating movement trajectories, producing image patches from the trajectories, and using the sampled image patches to train and perform angle classification tasks. See Fig. 3 for an overview of the experiment.

A. Generating Saccadic Eye Movement Trajectories

The first step in the pipeline involves using the 2D-OPMM model to generate the trajectories of six different SEM types, corresponding to the six different orientations: $0°$, $30°$, $60°$, $90°$, $120°$, and $150°$ where angles are measured counterclockwise from the positive x-axis. The SEMs are generated with a set of amplitudes (in $°$ unit) applied to the extraocular muscles. The SEMs start from the original resting gaze $(0°, 0°)$ to the other end gaze and from that end gaze going back to the resting gaze. For example, a SEM with a maximum amplitude of $5°$ in $30°$ direction was produced by applying an amplitude of $+5°$ to the (lateral + medial) rectus muscles and an amplitude of $+3°$ to the (superior + inferior) rectus muscles with the onset position at the resting gaze $(0°, 0°)$. Next, an amplitude of $-5°$ was applied to the (lateral + medial) rectus muscles and another amplitude of $-3°$ was applied to the (superior + inferior) rectus muscles from the gaze $(5°, 3°)$ to drive the eye back to the original resting position.

We ran the 2D-OPMM algorithm six times to produce six different sets of data with different maximum amplitudes ($5°$, $10°$, $15°$, $20°$, $25°$, and $30°$) where each set contain six different trajectory types (in $0°$, $30°$, $60°$, $90°$, $120°$, and $150°$ direction). All SEMs were produced within 200 milliseconds duration. The amplitudes were chosen between $[-30°, 30°]$ because of the limit of the eye's angular span and the accuracy of the 2D-OPMM. The greater the amplitudes are, the more differences between actual eye trajectories and simulated trajectories, due to non-linearity of the real oculomotor plan [21]. Fig. 4 shows the resulting trajectories of the saccades.

B. Sampling Images from The Eye Movements Trajectories

The next step in the pipeline is to generate training image patches from natural (and synthetic) images, using the trajectories in the previous step. The natural image set contained six different images which describe natural objects with linear features along with various orientations corresponding to the six orientations to be tested. To generate an image patch e.g. $30°$ orientation with a maximum amplitude (analogous to the force applied to the ocular muscle) of $5°$ image patch, we first align the corresponding SEM trajectory to the centerline of the $30°$ orientation feature in the given image. Next, we use a sliding window to trace along the trajectory to collect the image samples (the image patches). We considered each point on the $30°$ SEM trajectory as the center of a square window ($225\ pixel \times 225\ pixel$) and collected all the pixels within that window to produce an image sample. Each trajectory contained 400 points; therefore, 400 image samples were produced for each oriented feature in the image. The process is repeated for all other SEM trajectories (i.e. $0°$, $60°, 90°, 120°$, and $150°$) and for all other maximum amplitudes (i.e. $10°$, $15°$, $20°$, $25°$, and $30°$). In total, there were six training datasets corresponding to the six different maximum amplitudes with each dataset containing samples for all six orientations (each orientation with 400 samples). Fig. 5 illustrates the sampling method we used to generate the training image patches from the SEM trajectories with a maximum amplitude of $5°$.

Note that since we are primarily interested in the learnability of the orientation from these image patches, and the sampling is dense along the eye movement trajectories, we do not need a separate test set to measure the generalization performance. Therefore, the whole dataset including 2,400 images (400 images per orientation) was randomly divided into three sets: training (70%), validation (15%), and testing (15%). Finally, as a baseline, we repeated the above procedure on a different image set with six artificial objects (just straight oriented lines) to compare the outcome of the oblique effect in laboratory conditions typically used in the psychophysics literature.

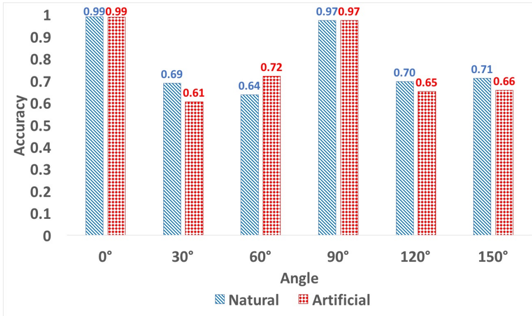
C. Learning to map image patch to orientation angle

In the final step, we used the datasets to train the MLP and observe the accuracy (Matlab Neural Network Toolbox was employed for this purpose). We ran the algorithm ten times for each maximum amplitude and considered the average recognition accuracy of the angles as the performance of the MLP on those angles for that maximum amplitude (Fig. 6b shows the results for both natural and artificial images). Results are summarized in Fig. 6a.

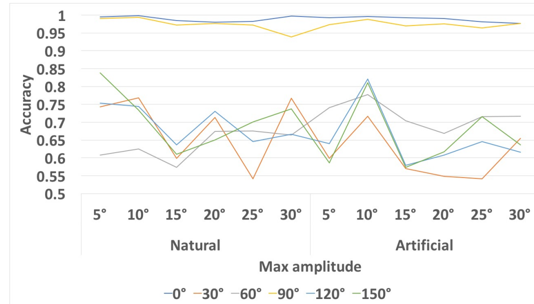
The results in Fig. 6 show the performance on oblique angles ($30°$, $60°$, $120°$, and $150°$) was much lower than that on the horizontal and vertical angles ($0°$ and $90°$). Recognition accuracy for vertical and horizontal angles was very consistent and ranged from 90% to 100%, while recognition rates for oblique angles were more variable and ranged from 50% to 80%. Also shown in Fig. 6, there were no significant differences between natural and artificial inputs. Table I provides a statistical summary of the results.

V. Discussion

The main contribution of this study to point to the oculomotor mechanics and the resulting sampling bias as the fundamental cause of the oblique effect. Note that one might argue there is no visual perception during saccades due to the visual saccadic masking phenomenon [28] which says



(a) Average recognition rate for each angle

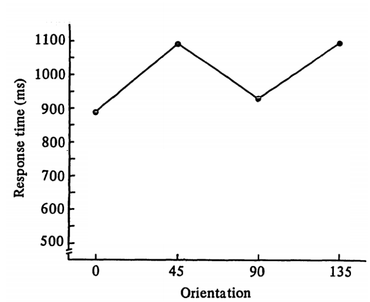


(b) Recognition rate for each angle with different max amplitudes

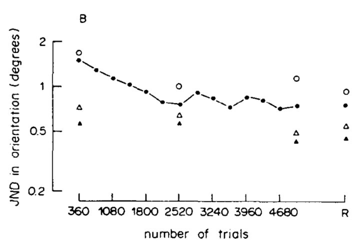
Fig. 6: **Performance of the multilayer perceptron in recognizing the angles.** Recognition accuracy (in percentage %) of the classifier for each angle. (a) shows the average performances of the classifier for each angle for both natural objects and artificial objects (straight oriented lines). (b) shows the performance of the classifier in recognizing each angle for each max amplitude (analogous to the force applied to the ocular muscles during the saccade) for natural vs. artificial input.

	Natural Objects						**Artificial Objects**					
	0°	**30°**	**60°**	**90°**	**120°**	**150°**	**0°**	**30°**	**60°**	**90°**	**120°**	**150°**
μ	98.96	68.91	63.70	97.40	69.60	71.21	98.85	60.52	72.08	97.43	65.17	65.67
σ	0.84	9.57	4.17	1.95	5.25	7.91	0.78	6.84	3.62	0.8	8.61	9.04
CI Lower	98.08	58.86	59.33	95.35	64.09	62.91	98.03	53.33	68.28	96.59	56.14	56.19
CI Upper	99.83	78.96	68.07	99.45	75.11	79.51	99.66	67.70	75.88	98.28	74.21	75.15

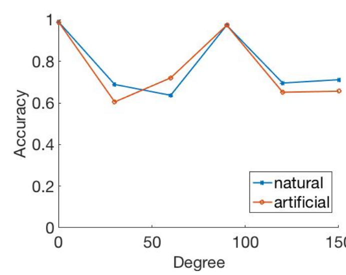
TABLE I: **Statistics collected from the experiment for natural objects.** μ: mean, σ: standard deviation, CI Lower + Upper: 95% confidence interval lower and upper bound. The unit is percentage (%) accuracy.



(a) Results from [12].



(b) Results from [27].



(c) Our result.

Fig. 7: **Comparison between results from human subject studies and our computational study.** (a) Line orientation identification results from [12] where 4 males and 4 females were asked to identify the orientation patterns and their response (reaction) time was recorded (the lower the better). (b) Line orientation discrimination results from [27] where 13 subjects with normal or corrected vision were asked to perform the discrimination task with extensive number of trials. The just noticeable differences (JND, the lower the better) and the number of trials were recorded. Closed circles: practiced oblique, open circles: non-practiced oblique, closed triangles: horizontal orientation, and open triangles: vertical orientations. (c) Our experimentation results for both natural and artificial objects (the higher the better).

the brain blocks visual processing whenever our eyes move. However, this theory is controversial, and the thought that we are blind during saccades is generally known as a common false belief since recent research shows vision does not shut down during eye movements [29]. Work of Burr et al. [30], Castet et al. [31], and Ross et al. [32], also indicated that saccadic masking happens only on several types of stimuli but not all. While saccadic masking does occur in patterns modulated at low spatial frequencies (low details and blurry parts), patterns of higher spatial frequency (high details parts) were not affected, and even enhanced during saccades.

Using the proposed hypothesized model, we were able to reproduce the oblique effect in a simulated visual orientation perception task. Our results suggest that imprecise and variable eye motions along the diagonal directions lead to a more variable sampling of oriented inputs, which then leads to reduced performance in orientation perception for diagonal inputs. Our computational results match results collected from human subject studies [12] and [27], where line orientation judgment/identification performances in vertical and horizontal orientation were significantly higher than those of obliques

(Fig. 7).

Our results suggest that in general motor output can play a significant role in determining the efficiency in perceptual performance. This idea is supported by the finding in [33] which showed that for tasks requiring high levels of precision, optimal perceptual performance would be achieved if the noise present is at the minimum level so that motor output can be accurately performed [33]. One prediction of our model is that the oblique effect can be reduced with more motor practice (cf. [34]). Also, it is known that more accurate visual sampling improves recognition accuracy as shown in [27] where line orientation discrimination improves with practice with oblique orientation lines. Another prediction from our experiment is that more abrupt saccades (higher max amplitude) can lead to more emphasized oblique effect. We expect that these predictions can be validated through psychophysical experiments. A promising future direction is to train visual cortical development models (such as LISSOM [17]) on the samples generated from our experiment and observe if structural and functional divergence emerges (e.g. differential representation of horizontal or vertical orientation vs. diagonal orientation [15], [16]).

VI. Conclusion

In this paper, we put forth a potential explanation for the origin of the oblique effect. To our knowledge, this is the first study to provide a mechanistic explanation of this effect and a computational argument based on sampling bias. The main idea is that due to the oculomotor mechanics of eye movement, saccade trajectories deviate more from the centerline along the diagonal orientation than the horizontal or vertical, thus leading to more variable sampling in the diagonal orientation. Due to this, the learnability of the diagonal orientation class is lower than the horizontal/vertical class, which is confirmed by training a multilayer perceptron. These results accurately reproduce the perceptual oblique effect.

ACKNOWLEDGMENT

The authors wish to thank Dong-hwa Shin for helping with some of the early figures in this paper. Natural images were taken from www.pixabay.com with CC0 Public Domain.

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