Decomposing the Response Time in Amblyopia: A Drift Diffusion Model Analysis

Xiaowei Ruan,[1] Liang Lin,[1] Xiaoxiao Ying,[2] Hanyi Zhang,[1] Junli Yuan,[1] Cheng Li,[1] Yan Yang,[1] Jinli Zhu,[1] Ruyin Chen,[1] and Fang Hou[1]

[1]School of Ophthalmology & Optometry and Eye Hospital, Wenzhou Medical University, Wenzhou, Zhejiang, China
[2]Cixi People's Hospital, Cixi, Zhejiang, China

Correspondence: Fang Hou, 270 Xueyuan Xi Road, Room 1707 Building No. 2, Wenzhou, Zhejiang 325027, China; houf@mail.eye.ac.cn.

XR and LL contributed equally to the work presented here and should therefore be regarded as equivalent authors.

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Purpose. Amblyopes are known to have delayed response times (RT) in various visual tasks. We aim to investigate whether any factor other than the sensory deficit contributes to the delayed RT in amblyopia.

Method. Fifteen amblyopic (26.0 ± 4.50 years) and 15 normal (25.6 ± 2.90 years) participants took part in this study. The responses and RTs in an orientation identification task were collected for each participant with stimulus contrast adjusted to the multiples of individual's threshold. A drift diffusion model was used to fit to the response and RT data and to estimate the RT components.

Result. There was a significant difference in the RT between the amblyopic and normal groups ($F(1, 28) = 6.75$, $P = 0.015$) but no difference in the accuracy ($F(1, 28) = 0.028$, $P = 0.868$). The drift rate function in the amblyopic eye had a larger threshold ($P = 0.001$) and shallower slope ($P = 0.006$) than that of the fellow eye. The amblyopic group has a longer non-decision time than the normal group ($F(1, 28) = 8.02$, $P = 0.008$). The drift rate threshold correlated with the contrast sensitivity ($P = 1.71 \times 10^{-18}$) but the non-decision time did not ($P = 0.393$).

Conclusions. Both sensory and post-sensory factors contributed to the delayed RT in amblyopia. The effect of the sensory loss in V1 on RT can be compensated by increasing stimulus contrast, and the post-sensory delay provides evidence for higher-level deficits in amblyopia.

Keywords: amblyopia, decision-making, response time, drift diffusion model, contrast sensitivity

Amblyopia, characterized by impaired visual acuity without any apparent structural or pathologic abnormalities, is a developmental visual disorder.[1,2] Besides the impaired spatial vision, amblyopic patients also show deficits on a range of other visual tasks, including stereopsis,[3] global motion perception,[4,5] and contour integration.[6–8] It is believed that amblyopia affects not only the primary visual cortex (V1)[9,10] but also the brain regions downstream of V1.[11,12]

A manifestation of the abnormality in amblyopia is the significantly delayed response time (RT) in visual tasks.[13–19] Although it is believed that the delayed RT in amblyopia is mainly due to the sensory deficit,[14,20] it is still not very clear whether there is any other factor that contributes to the delay. Using a version of the Landolt C gap discrimination task with very strong stimuli, Farzin and Norcia[18] showed that the RT in both the amblyopic or non-amblyopic eyes were delayed, and they suggested that the result reflected the deficit at a higher-level brain region other than the visual cortex. On the other hand, in a case study, Gambacorta et al.[21] measured the RT as a function of stimulus contrast in a small sample of amblyopes and estimated the RT asymptote at high contrast. They found that some of the amblyopes have an irreducible manual and saccadic response delay in their amblyopic eyes relative to the fellow eyes and suggested that the delay was due to a central deficit of directing actions to a target. However, these conclusions were based on the same assumption that the time for sensory processing could be fully compensated at high stimulus levels, which has not been rigorously examined. The RT reflects the total time that the visual system needs for processing of sensory signals, formation of a decision based on the incoming sensory evidence, and planning of a motor response.[22,23] Without strict quantification of the RT components that correspond to these different processes, it is impossible to make any decisive conclusions regarding what exactly cause the prolonged RT in amblyopia.

The drift diffusion model (DDM)[23,24] could provide a theoretical framework to decompose the RT data in amblyopia. The DDM assumes that the observer makes choices in a perceptual task by accumulating the sensory evidence (Fig. 1A). In each trial, the evidence-based decision variable starts at z and increases at a certain accumulation rate v, until the total evidence reaches one of the two boundaries, 0 or a. After hitting the boundary, a response is generated. The drift rate v is determined by the quality of the sensory

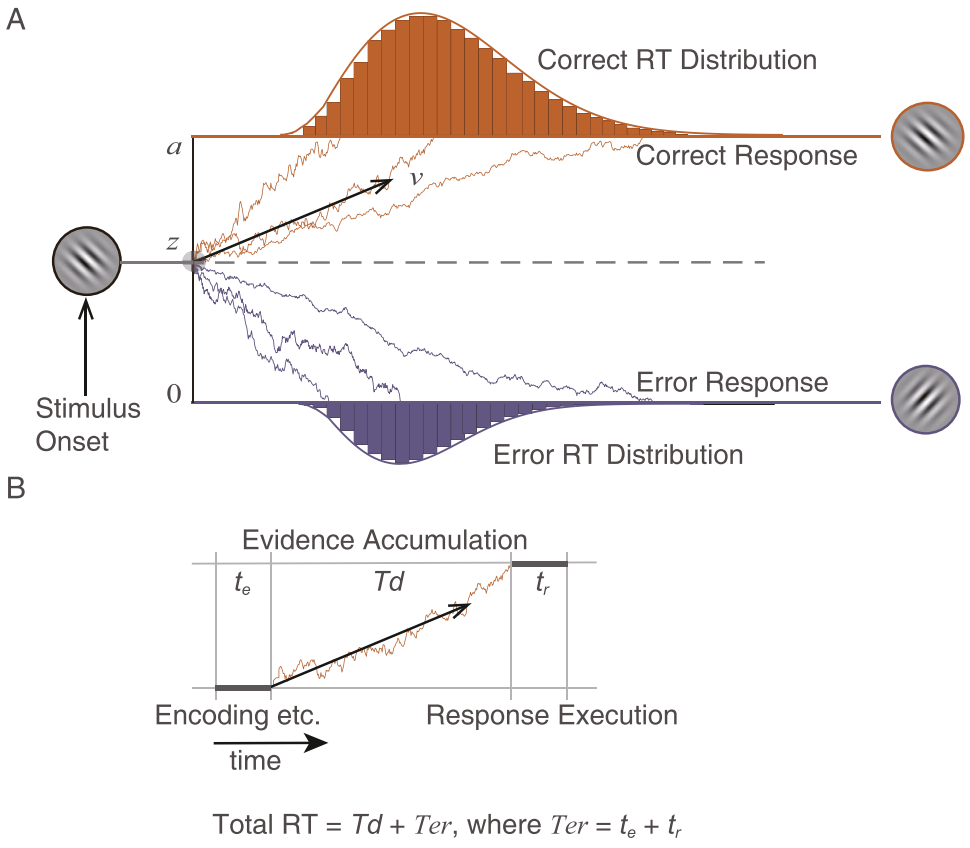

Figure 1. The illustration for the DDM. (**A**) In each trial, the evidence-based decision variable starts at z, and increases at a certain accumulation rate v, until the total evidence reaches one of the two boundaries, 0 or a. After hitting the boundary, a response is generated. The accumulation is contaminated by Gaussian noise with mean zero and standard deviation s. With different v and the impact of noise, the process approaches the boundary at different time and sometimes reaches the wrong boundary. Six sample paths are shown. (**B**) The total RT consists of the time for the evidence accumulation (*Td*) and the time taken by all non-decision components such as the stimulus encoding and response execution (*Ter*).

information and the information accumulation process is contaminated by Gaussian noise with mean zero and standard deviation s. Therefore the process approaches the boundary at different time and sometimes reaches the wrong boundary. It resembles the random trajectory of a Brownian particle; hence, the name. The total RT is the sum of the time taken by the accumulation processes (*Td*) and the time for stimulus encoding and response execution (*Ter*, Fig. 1B). The DDM can well account for the RT distribution for the correct and incorrect responses and is supported by animal studies on how the brain implements a perceptual decision task.[22,25,26] This model has been widely used in psychology, neuroeconomics, and neuroscience[27–30] and would be suitable for analyzing the RT in amblyopia.

To answer (1) whether increasing the stimuli strength can fully compensate the sensory-related processing time, and (2) whether there is any other factor that contributes to the delayed RT, we conducted this study. We asked the amblyopic and normal participants to perform an orientation identification task and recorded their RTs and responses under different contrast conditions. To equate the effective contrast of the stimulus in the amblyopic and normal eyes, we set stimuli contrasts to the multiples of each eye's contrast threshold. We then applied the DDM to fit the RT distributions of the correct and incorrect responses, and extracted the RT components for each participant. Detailed comparisons were made between the two groups.

Material and Methods

Participants

Fifteen amblyopic patients aged from 18 to 37 years (26.0 ± 4.50 years) and fifteen normal college students aged from 22 to 33 years (25.6 ± 2.90 years) took part in this study. The amblyopic participants were recruited at the Eye Hospital, Wenzhou Medical University and the normal participants were recruited in the campus of Wenzhou Medical University. All participants went through detailed ophthalmological examinations by an ophthalmologist (LL, the second author). Characteristics of the amblyopic participants are listed in Table 1. A2 and A7 were strabismic amblyopia, and their eye positions have been surgically corrected. All normal participants had corrected-to-normal vision and showed no sign of any eye disease. Their eye dominance was determined by the hole-in-card method.[31] The study was approved by the institutional review board of human subject research of the Eye Hospital, Wenzhou Medical University and adhered to the tenets of the Declaration of Helsinki.

Table 1. Clinical Details of Amblyopic Participants

Participant	Sex	Type	Age	Visual Acuity (logMAR)	Refractive Error
A1	Male	Aniso	25	R: 0.42	R: −16.00/−1.00 × 180
				L: −0.10	L: −7.50/−0.75 × 10
A2	Male	Strab	31	R: 0.40	R: 1.00/−0.50 × 45
				L: −0.10	L: −0.75
A3	Male	Aniso	24	R: −0.10	R: −1.75/−0.50 × 160
				L: 0.46	L: 3.50/−12.5 × 170
A4	Male	Aniso	29	R: −0.16	R: 0.25
				L: 0.22	L: 1.00/−0.25 × 135
A5	Male	Aniso	27	R: −0.04	R: −4.00/−1.25 × 18
				L: 0.32	L: 0.25
A6	Female	Aniso	25	R: −0.04	R: plano
				L: 0.64	L: 4.50/−0.75 × 15
A7	Female	Strab	24	R: 0.00	R: −4.75/−0.25 × 175
				L: 0.20	L: −4.75/−0.25 × 154
A8	Male	Aniso	22	R: −0.10	L: −4.00
				L: 0.60	R: 5.00
A9	Male	Aniso	37	R: 0.74	R: 5.50/1.00 × 170
				L: 0.00	L: −2.50/−0.50 × 90
A10	Female	Aniso	21	R: 0.02	R: −1.50/−4.50 × 180
				L: 0.14	L: 1.00/−6.50 × 174
A11	Male	Aniso	18	R: 0.20	R: 4.00/−1.75 × 179
				L: −0.10	L: −0.50/−0.50 × 170
A12	Female	Aniso	26	R: 0.20	R: −5.75/−3.00 × 75
				L: −0.10	L: −6.00
A13	Female	Aniso	29	R: 0.68	R: 2.25
				L: 0.00	L: −0.75 × 70
A14	Female	Aniso	29	R: −0.10	R: −0.50
				L: 0.26	L: 2.75/−1.0 × 158
A15	Female	Aniso	23	R: −0.20	R: −2.00
				L: 0.18	L: 2.00

Aniso, anisometropia; Strab, strabismus; L, left; R, right.

All participants provided written informed consent and were naive to the purpose of the study.

Apparatus

The program used in the experiment was written in MATLAB (The MathWork Corp, Natick, MA, USA) with Psychtoolbox and run on a PC computer. Stimuli were displayed on a gamma-corrected monitor (ASUS SWIFT PG278QR; Asustek Computer Inc., Taipei, Taiwan) with 2560 × 1440 pixels resolution and a vertical refresh rate of 120 Hz and viewed at 1.44 m. The RT Box, which has its own clock and microprocessor for high-precision button event detection,[32] was used to record the RT and response. A chin rest was used to minimize head movement during the experiment. Observers viewed the stimuli monocularly with their best correction (if any) in a dark room.

Stimuli

The stimuli were sinusoidal gratings oriented either 45° or −45° from vertical. A half-Gaussian envelop was used to remove the abrupt edges of the gratings. To equate the visibility (effective contrast) of the stimulus in the amblyopic and normal eyes, we set the grating spatial frequency to 1 cycle per degree (cpd) and the stimuli contrast to the multiples of each eye's contrast threshold. Because it has been reported that some individuals showed attenuation across the whole contrast range, whereas others showed constancy at high contrast,[33,34] five different levels of contrast were used in the experiment to estimate how the RT changes with the stimulus contrast. Specifically, the stimuli contrasts were 0.85, 0.95, 1.05, 1.15, and 1.25 log threshold units (LTU).

Design

The contrast sensitivity functions (CSF) in the amblyopic (AE) and fellow eyes (FE) of the amblyopic participants and those in the non-dominant (NDE) and dominant eyes (DE) of the normal participants were measured using a Bayesian adaptive procedure (the quick CSF method) with sinewave gratings, the description of which can be found elsewhere.[35,36] The contrast threshold at the spatial frequency of 1 cpd was derived from the CSF and used to determine the stimuli contrasts in the following experiment for each participant.

Then the participants were asked to perform an orientation identification task. In the task, they were told to indicate as quickly as possible whether the Gabor stimulus was oriented to the left or to the right from vertical by pressing the corresponding buttons on the RT Box. The response and RT of the participant under five stimulus contrast conditions were measured. Different contrast conditions, each of which had 100 trials, were intermixed randomly in one session. The session was divided into 10 blocks of 50 trials. Participants were encouraged to take breaks between blocks. One session lasted about 30 minutes.

All participants were tested monocularly while the untested eye was occluded with an opaque eye patch. The two eyes of a participant were tested in two separate sessions

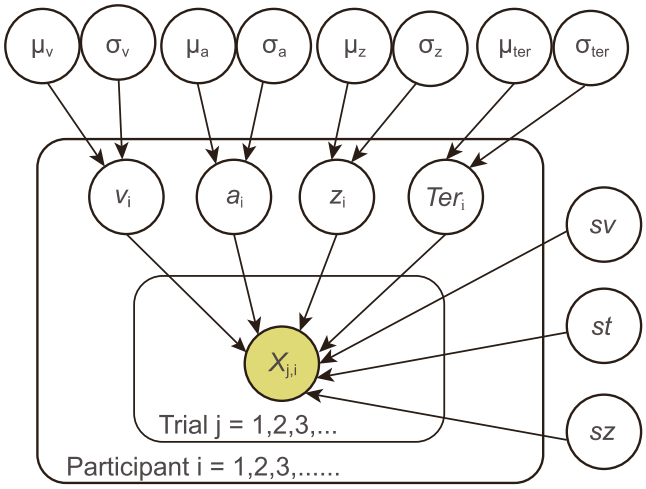

Figure 2. Illustration of the hierarchical DDM. $X_{j,i}$ inside of the *yellow circle* is the observed data including the RT and response (correct or incorrect) at trial *j* for participant *i*. $X_{j,i}$ is determined by the decision parameters including drift rate (v_i), boundary (a_i), starting point (z_i), and non-decision time (Ter_i) of participant *i*. Individual parameters are drawn from the group, which follows a Gaussian distribution with group mean μ and variance σ. *Sv*, *st*, and *sz* represent trial-by-trial variability of *v*, *z*, and *Ter*, respectively, and are shared by participants in the same group.

in a random order. Before the test started, each participant was given five minutes to adapt to the dim test environment and a practice session of about 100 trials.

Procedure

Each trial began with a brief tone signaling its onset and a presentation of crosshair fixation (250ms) at the center of the screen. After a 125 ms blank screen, a grating stimulus was presented. The grating remained on the screen until observer responded or for a maximum duration of 800 ms. The RT from the stimulus onset to the time at which participant pressed the buttons was recorded. The free viewing paradigm allowed us to accurately infer the DDM parameters.[23,37] Auditory feedback was provided after each response. A new trial started 500 ms after the response.

Model Fitting

To extract the RT components, a hierarchical DDM was constructed to account for the RT distributions of the correct and incorrect responses in the task for each participant. The RTs shorter than 200 ms or longer than 800 ms were discarded in the analysis, because the responses with RTs below 200 ms are likely to be fast guesses,[38] and RTs above 800 ms indicate the violation of evidence accumulation in DDM, probably because of an attentional lapse.[39] In total, less than 5% of RT data were discarded.

In the hierarchical DDM, the RT and response of individual participant is determined by the decision parameters (i.e., drift rate [v_i], boundary [a_i], starting point [z_i], and non-decision time [Ter_i]). On top of that, the parameter of individual participant is randomly drawn from the corresponding (amblyopic or normal) group distributions, which are determined by corresponding hyper parameters (Fig. 2). The intertrial variability parameters are shared by participants in the same group because their estimation is computationally expensive and it does not affect the precision of estimation.[40]

Table 2. Parameter Specification of the DDM Variants (M1 ~ M4)

Models	Whether Boundary Depends on Eye	Whether Non-Decision Time Depends on Eye	DIC
M1	Yes	Yes	−22,879
M2	Yes	No	−22,563
M3	No	Yes	−22,722
M4	No	No	−22,117

To account for the effect of stimulus contrast and eye on the DDM parameters, we assumed that the drift rate *v* depends on the stimulus contrast and eye as the rate is determined by the quality of the sensory evidence.[41–44] The starting point *z* was fixed at 0.5 because the participants had no preference of either choice in the orientation identification task. Because we were not sure whether the boundary *a*, or non-decision time *Ter* depends on the eye, four variants of DDM (M1 ~ M4), corresponding to all possible cases where the parameter of *a* or *Ter* depends on eye or not, were constructed. The specifications of the model variants are listed in Table 2. The hierarchical DDM variants were fit to the data of the amblyopic and normal group separately. A Python package, HDDM[40] was used in fitting. The deviance information criterion (DIC), a common measure for evaluating model fit in hierarchical models (lower is better),[45] of each model variant for the two groups was computed. The DDM variant with the smallest DIC was selected as the best model. The DDM parameters of the AE and FE of each amblyopic participant and the NDE and DE of each normal participant were extracted from the best fit DDM variant. Repeated measure ANOVA were used to compare the DDM parameters between the two groups.

Results

Contrast Threshold, RT, and Accuracy

The average contrast thresholds at 1 cpd for the two eyes in the amblyopic and normal groups are shown in Figure 3A. Repeated measures ANOVA showed that no significant effect was found of group ($F(1, 28) = 0.077$, $P = 0.783$, $\eta_p^2 = 0.003$) or eye ($F(1, 28) = 3.70$, $P = 0.065$, $\eta_p^2 = 0.117$). There was a significant interaction between eye and group ($F(1, 28) = 6.64$, $P = 0.016$, $\eta_p^2 = 0.192$). The FE showed a lower contrast threshold than the AE ($P = 0.004$) and DE ($P = 0.005$).

The average accuracies for the two eyes in the amblyopic and normal groups are plotted against the stimulus contrast (in LTU) in Figure 3B. Repeated measures ANOVA was conducted to examine the effect of contrast, eye and group on the accuracy. There was a significant effect of contrast on accuracy ($F(3.67, 103) = 301$, $P = 1.37 \times 10^{-54}$, $\eta_p^2 = 0.916$). There was no significant effect of group ($F(1, 28) = 0.028$, $P = 0.868$, $\eta_p^2 = 0.001$), eye ($F(1, 28) = 0.052$, $P = 0.821$, $\eta_p^2 = 0.002$), or interactions between any two of the factors (all *P*s > 0.05). The result confirmed that the visibilities of the stimuli were equated in the two eyes and in the two groups.

The mean RTs for the two eyes in the amblyopic and normal group are shown as the function of the stimulus contrast (in LTU) in Figure 3C. Repeated measures ANOVA

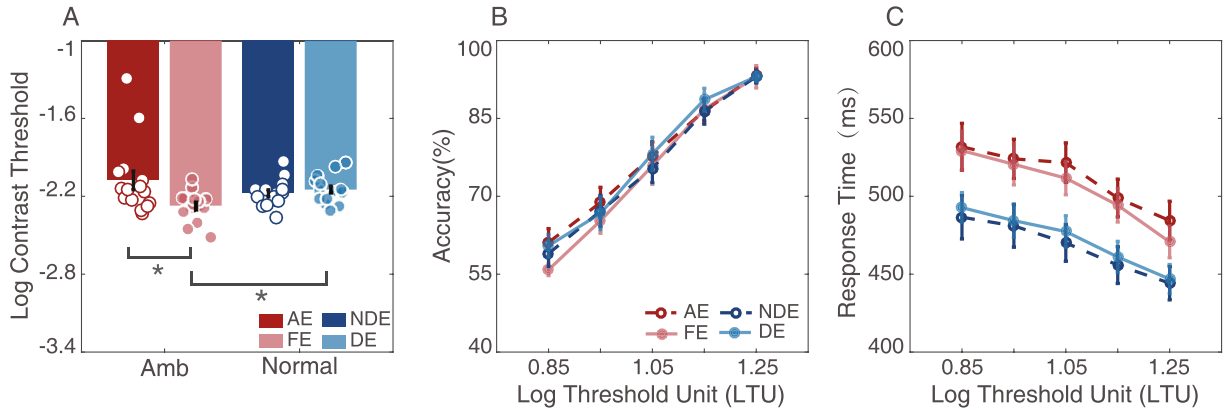

Figure 3. (**A**) The contrast threshold at 1 cpd of each eye in the amblyopia and normal groups. The average accuracy (**B**) and RT (**C**) at different stimulus contrast in the two eyes of the amblyopia and normal groups. *Dashed lines* represent the amblyopic or nondominant eye; *solid lines* represent the fellow or dominant eye. *Red*: the amblyopic group; *blue*: the normal group. *Error bars*: ±1 standard error. *$P < 0.05$.

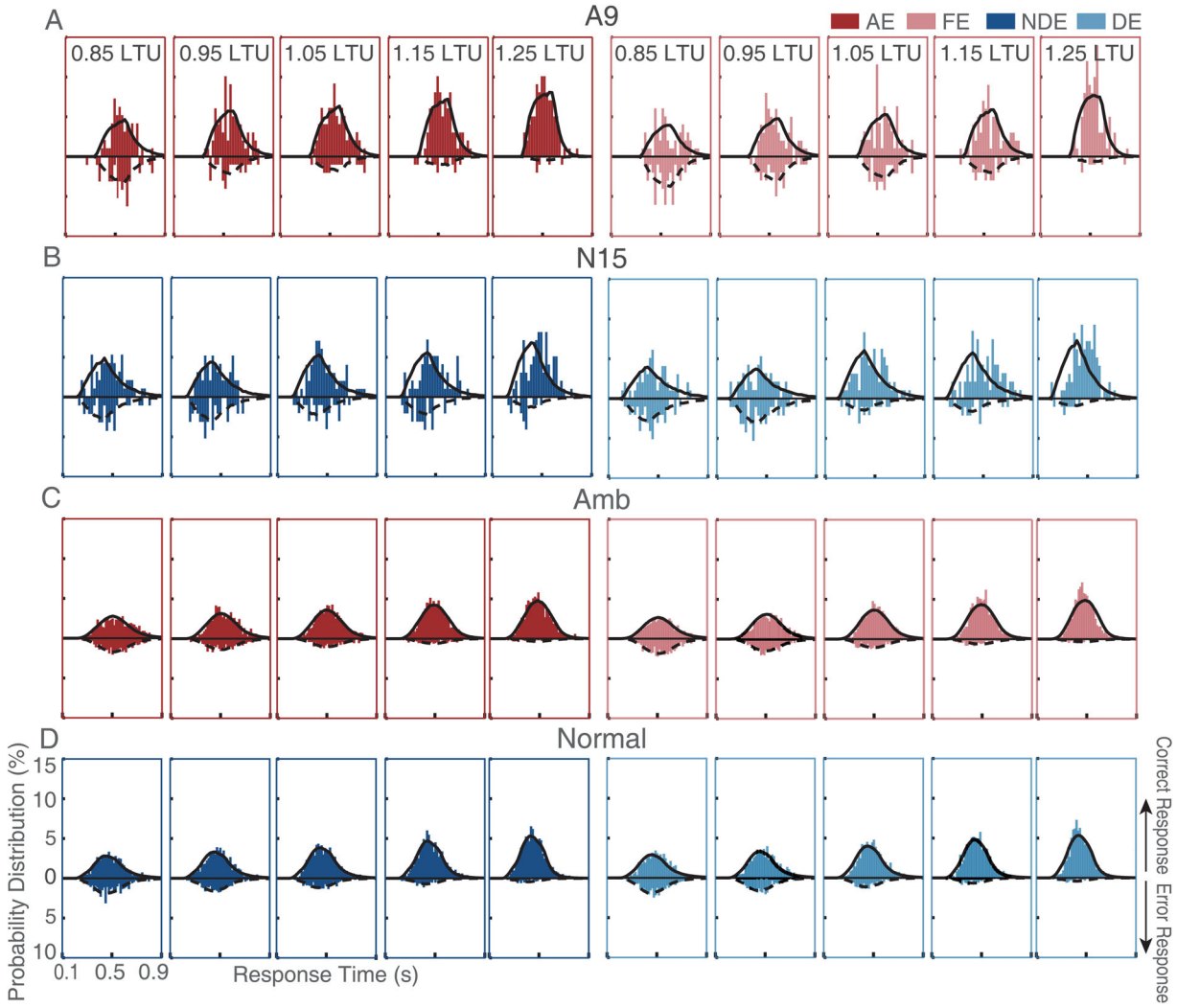

Figure 4. The empirical distributions of the RT for correct and incorrect responses under five contrast conditions are plotted together with the predicted RT distributions by the best DDM variant (M1) for each eye of (**A**) a representative amblyopic participant (A9), (**B**) a representative normal participant (N15), (**C**) the amblyopic group, and (D) the normal group, respectively. The RT distributions of the incorrect responses are flipped around the x-axis. Different colors indicate different eyes: *red*, AE; *pink*, FE; *blue*, NDE; *light blue*, DE. The histograms represent empirical data. The *continuous* and *dashed curves* represent model-predicted correct and incorrect response distributions, respectively.

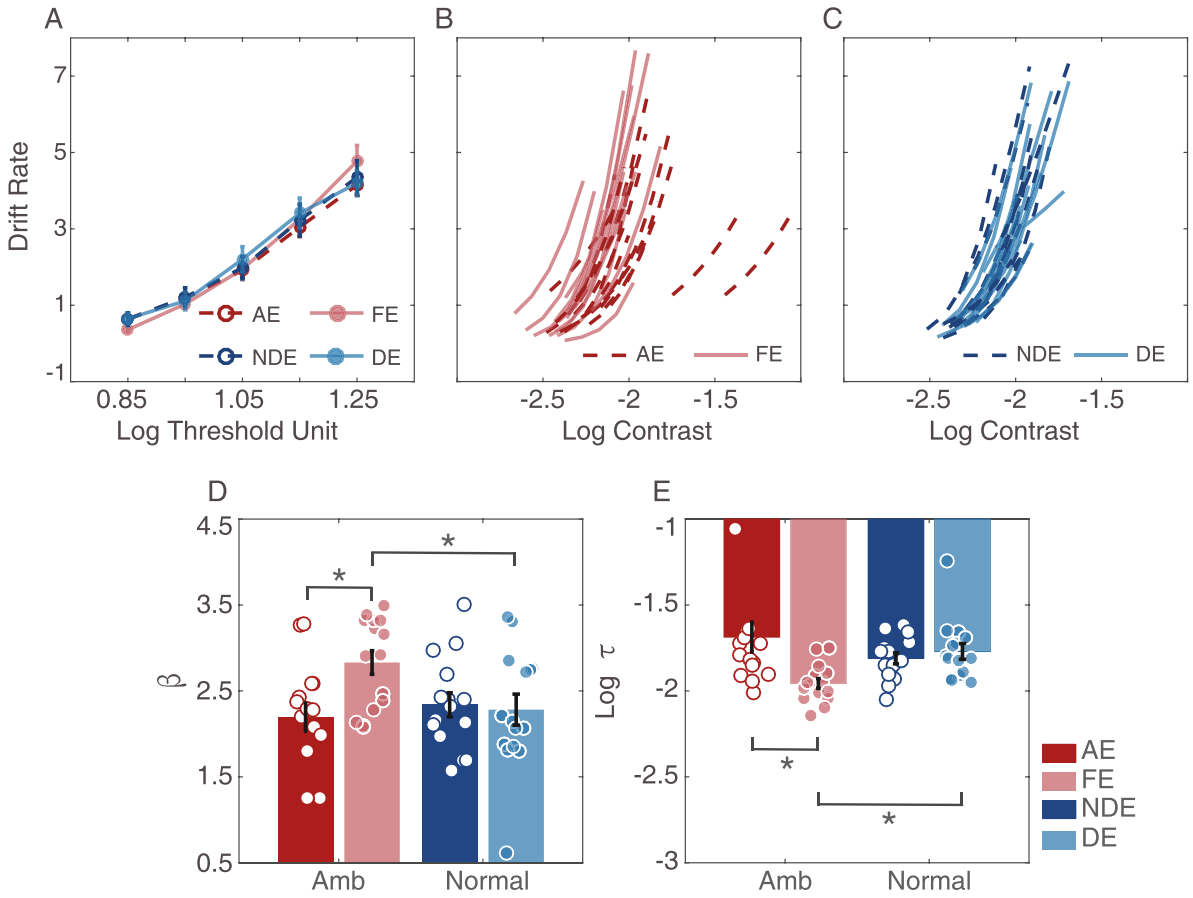

Figure 5. (**A**) The drift rate as a function of log threshold unit. (**B**) The drift rate as a function of actual contrast for the amblyopic and fellow eyes of each amblyopic participant. Red doted lines represent the amblyopic eyes. Pink solid lines represent the fellow eyes. (**C**) The drift rate as a function of actual contrast for the dominant and non-dominant eyes of each normal participant. Blue dash lines represent the non-dominant eyes. Light blue solid lines represent the dominant eyes. The slope β (**D**) and threshold τ (E) of the drift rate function (of actual contrast) for the two eyes in the two groups. *Red*, AE; *pink*, FE; *blue*, NDE; *light blue*, DE. *Error bars:* ± 1 standard error. *$P < 0.05$.

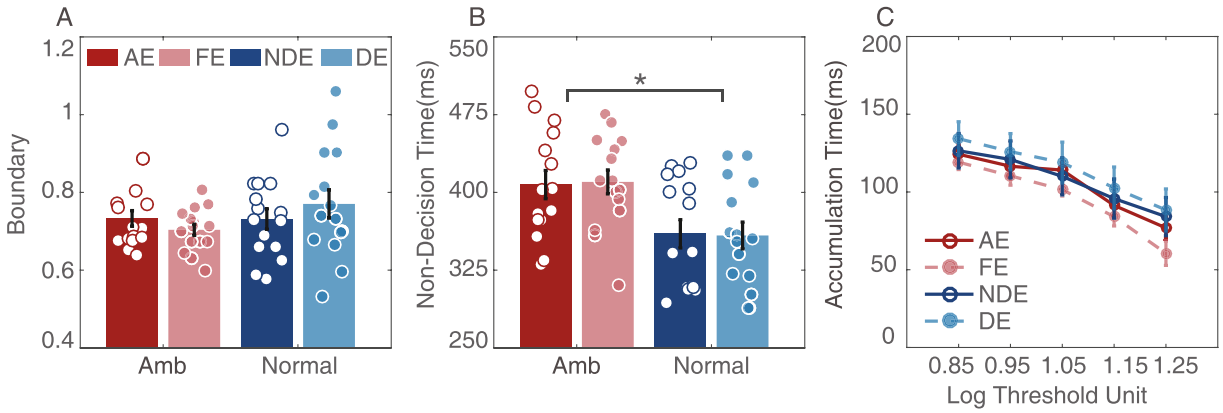

Figure 6. The boundary separation (**A**), non-decision time (**B**), and the accumulate time at different contrast levels (C) of the amblyopic and normal groups estimated from the best fit DDM are shown. *Red*, AE; *pink*, FE; *blue*, NDE; *light blue*, DE. *Error bar:* ±1 standard error. *$P < 0.05$.

revealed that there was a significant effect of the stimulus contrast on the RT ($F(1.70, 47.6) = 66.7$, $P = 1.51 \times 10^{-13}$, $\eta_p^2 = 0.704$), with shorter RT at higher stimulus contrast. A significant effect of group was also found ($F(1, 28) = 6.75$, $P = 0.015$, $\eta_p^2 = 0.194$). There was no significant effect of eye ($F(1, 28) = 0.0310$, $P = 0.862$, $\eta_p^2 = 0.001$) or of interactions between any two factors of the contrast, eye and group (all Ps > 0.05). The RT of the amblyopic group was significantly

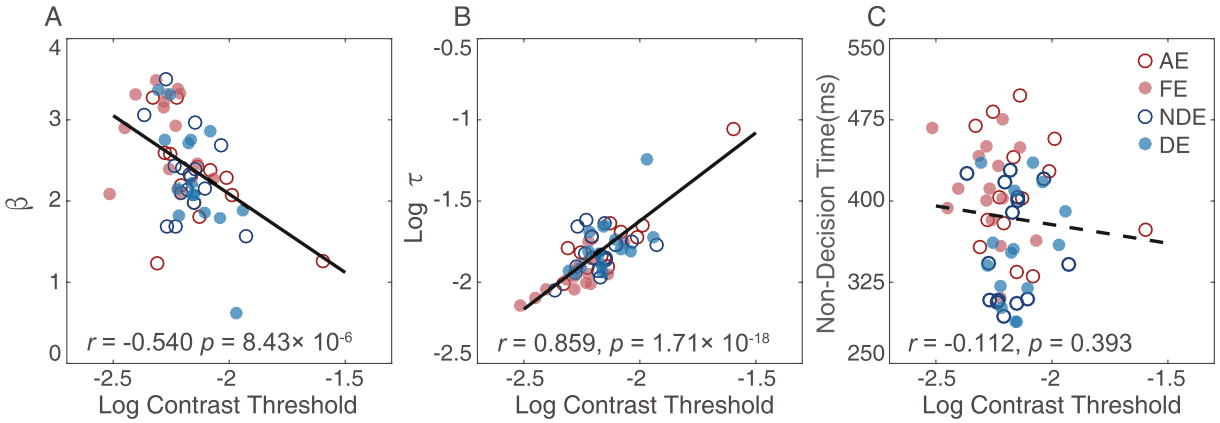

Figure 7. (**A**) The relationship between the slope β of the drift rate function and contrast threshold. (**B**) The relationship between the threshold τ of the drift rate function and contrast threshold. (**C**) The relationship between the non-decision time *Ter* and contrast threshold. The data were pooled across the two eyes for the amblyopia group. *Empty* and *filled circles* indicate the AE and FE for the amblyopic participants or the NDE and DE for the normal participants, respectively. *Red*, AE; *pink*, FE; *blue*, NDE; *light blue*, DE. *Solid* and *dashed lines* indicate statistically significant and insignificant correlations, respectively.

slower than that of the normal group (470 ± 40.5 ms vs. 508 ± 44.7 ms, $P = 0.015$), no matter which eye was used.

Model Fitting

The DICs of all DDM variants are listed in Table 2. The DDM variant M1 was the best model due to its lowest DIC value. It suggests that the decision boundary *a* and non-decision time (*Ter*) depended on the eye. The DDM variant M1 provided good fit to the observed data of all contrast conditions for the two eyes at both individual and group levels. To better illustrate the goodness of fit, we plot the empirical distribution of RT for the correct and incorrect responses along with the RT distribution predicted by M1 for two representative participants (A9 and N15) and for the two groups (pooled across individuals) in Figure 4, respectively. The following analyses were based on the parameters estimated from the best fit M1.

Parameters of the DDM

Figure 5A shows the drift rate v as a function of contrast (in LTU) estimated from M1 for the two groups. Repeated measures ANOVA showed that there was a significant effect of contrast on the drift rate v ($F(1.61, 45.1) = 224$, $P = 1.51 \times 10^{-22}$, $\eta^2_p = 0.889$) with greater v at higher stimulus contrast. There was no effect of eye ($F(1, 28) = 0.098$, $P = 0.756$, $\eta^2_p = 0.003$), group ($F(1, 28) = 0.058$, $P = 0.811$, $\eta^2_p = 0.002$). No interactions between contrast and group or contrast and eye were found (all Ps > 0.05). The interaction between contrast, eye, and group was significant ($F(3.43, 24.5) = 3.13$, $P = 0.024$, $\eta^2_p = 0.100$). The result again confirmed that the sensory input to the two eyes in the two groups were well controlled.

To further explore how visual input affects the drift rate, we plot the drift rate as a function of actual contrast in the two eyes for each amblyopic and normal participant in Figures 5B and 5C. It seems that the drift rate functions differ between the amblyopic and fellow eyes while those in the non-dominant and dominant eyes look similar. To quantify the difference, a modified Weibull function was used to fit each drift rate function with the following equation:

$$\text{drift rate}\,(cst) = 10 - 10 \times \exp\left(-\left(\frac{cst}{\tau}\right)^{\beta}\right),$$

where *cst* is the actual contrast, and β and τ are the slope and the threshold of the drift rate function, respectively. The τ represents the contrast that corresponds to the drift rate of 6.321. The upper asymptotic of the drift rate was set to 10.

The β and τ of the drift rate function of the two eyes were estimated from the best fitting modified Weibull for each participant, and are showed in Figures 5D and 5E. Repeated-measures ANOVA showed that there was no significant effect of eye ($F(1, 28) = 3.69$, $P = 0.065$ $\eta^2_p = 0.117$) or group ($F(1, 28) = 1.55$, $P = 0.223$, $\eta^2_p = 0.053$), but a significant interaction between eye and group on β ($F(1, 28) = 5.30$, $P = 0.029$, $\eta^2_p = 0.159$). The slope β in the FE was steeper than that in the AE ($P = 0.006$) and DE ($P = 0.022$). For the threshold τ, there was a significant effect of eye ($F(1, 28) = 5.60$, $P = 0.025$, $\eta^2_p = 0.167$), but no significant effect of group ($F(1, 28) = 0.277$, $P = 0.603$, $\eta^2_p = 0.010$). The interaction between eye and group was significant ($F(1, 28) = 10.2$, $P = 0.003$, $\eta^2_p = 0.267$). The drift rate threshold τ in the FE was lower than that in the AE ($P = 0.001$) and DE ($P = 0.002$). The drift rate function in the amblyopic eye had a higher threshold ($P = 0.001$) and shallower slope ($P = 0.006$) than that in the fellow eye.

The boundary separation *a* and non-decision time *Ter* estimated from M1 for two groups are shown in Figure 6. Repeated measures ANOVA showed that there was no significant effect of eye ($F(1, 28) = 0.075$ $P = 0.786$, $\eta^2_p = 0.003$), group ($F(1, 28) = 1.03$, $P = 0.319$, $\eta^2_p = 0.036$), or interaction between eye and group ($F(1, 28) = 3.79$, $P = 0.062$, $\eta^2_p = 0.119$) on the boundary separation *a*. The mean boundary separation *a* of all participants was 0.735 ± 0.100 (Fig. 6A).

For the non-decision time (*Ter*), there was a significant effect of group ($F(1, 28) = 8.02$, $P = 0.008$, $\eta^2_p = 0.223$). There was no significant effect of eye ($F(1, 28) = 0.008$, $P = 0.928$, $\eta^2_p = 2.98 \times 10^{-4}$) or the interaction between eye and group ($F(1, 28) = 0.\ 149$, $P = 0.703$, $\eta^2_p = 0.005$). The

non-decision time *Ter* in the amblyopic group was longer than that in the normal group (409 ± 48.2 ms vs. 359 ± 50.6 ms, $P = 0.006$, Fig. 6B).

We also calculated the accumulation time (*Td*) by subtracting *Ter* from the RT (Fig. 6C). Repeated measures ANOVA showed except a significant effect of contrast ($F(1.70, 47.6) = 66.7$, $P = 1.51 \times 10^{-13}$, $\eta^2_p = 0.704$), there was no significant effect of eye, group, or interactions among these factors on *Td* was found (all *P*s > 0.05). The result confirmed that increasing the stimulus contrast could compensate the accumulation time.

The Relationship Between the DDM Parameters and Sensory Deficit in Amblyopia

In the DDM, the drift rate which represents the evidence gathered by the visual system per unit time depends on the quality of sensory information whereas the non-decision time does not. Therefore we explored the relationships between the contrast threshold at 1 cpd and DDM parameters, including the slope β and the threshold τ of the drift rate function, as well as the non-decision time *Ter* in combined data from the amblyopic group and normal group together. In Figures 7A and 7B, the slope β and the threshold τ of the drift rate function are plotted against the contrast threshold at 1 cpd, respectively. There was a strong correlation between the slope β and contrast threshold ($r = -0.540$, $P = 8.43 \times 10^{-6}$) and between the drift rate threshold τ and contrast threshold ($r = 0.859$, $P = 1.71 \times 10^{-18}$). In contrast, no significant correlation between the non-decision time and contrast threshold was found ($r = -0.112$, $P = 0.393$; Figure 7C). The results were similar when the data of the amblyopic group were analyzed alone.

Discussion

In this study, we measured the RTs and responses of the amblyopic and normal participants in an orientation identification task under five contrast conditions. We found that when the stimulus visibilities were matched in threshold units, the RTs in amblyopic group were significantly longer than that in the normal group, no matter which eye was used. By fitting four DDM variants to the RT distributions of the correct and incorrect responses, we determined the best fit DDM variant. The best-fit model suggested that the drift rate function in the amblyopic eye had a higher threshold and shallower slope compared to the fellow eye. Besides, the non-decision time in the amblyopic group was found to be significantly longer than that in the normal group. There was no significant difference in the decision boundary between the two groups. With correlation analyses, we found that the drift rate function was highly correlated to the contrast threshold, and the non-decision time was independent of the contrast threshold.

We found that the stimulus contrast had significant effect on the RT in both amblyopic and normal groups, which is consistent with previous finding that the visual latency varies with the luminance and contrast of a stimulus.[46] When the stimulus contrasts were equated in threshold units, the RTs in the amblyopic and fellow eyes were comparable. This result is consistent with previous studies, where it was found that when the sensory differences between the two eyes were minimized, the RTs of anisometropic amblyopes were similar in the two eyes.[15,21] In addition, the RTs in both AE and FE were significantly longer than those in the NDE and DE, which is in line with the result in Farzin and Norcia.[18]

The RT reflects the total time that the hierarchical processes of visual system take to generate a response from a visual input. It is information-rich and can provide critical information regarding the underlying mechanisms of visual deficits. However, without proper analysis, the information may not be fully be exploited. The DDM is a powerful tool to extract the information from the RT data. The theoretical model of the perceptual decision making other than a descriptive approach provided a framework for us to use behavioral measurements including both correct and incorrect RTs to infer the components of RT. According to the DDM, the RT consists of two major components: the sensory-dependent decision time that taken by the evidence accumulation process and the sensory-independent non-decision time for stimulus encoding and response execution.[23,24] The DDM has been supported experimentally in many studies. For example, people have found the neural activities that correspond the evidence-related accumulation in the lateral intraparietal cortex and the prefrontal cortex.[47–49] The asymptotic time of RT under strong stimulus condition in human and animal studies[21,50] could be seen as the non-decision time. By fitting the DDM to the RT distributions for both correct and error responses of the amblyopic participants, we were able to separate the two RT components: the drift rate function and the non-decision time *Ter*.[23,24]

The drift rate function converts the visual input into the evidence for decision making. Both the slope and threshold were found to correlate with the contrast sensitivity in the amblyopic group. This confirms that the drift rate, or the momentary information quality, depends on the sensory input. People suggested that the drift rate in the DDM was related to the discriminability of the visual system in the Bayesian sequential probability ratio test model.[51,52] Thus the drift rate is determined by both the signal and noise of the visual system. When viewing stimuli with same strength, the drift rate would be smaller because of the higher internal noise in the amblyopic visual system.[53–55] This could explain the linear relationship between the visual acuity and the RT deficits in the amblyopic eye reported in other studies.[14,20] On the other hand, it suggests that the drift rate can be compensated by increasing the stimulus strength, as confirmed by our finding of no difference in the drift rate or accumulation time between the AE and NDE.

It is worth noting that our result does not necessarily suggest that the decision-related accumulation occurs in the primary visual cortex.[47–49] Instead, the drift rate function, when affected, could be the result of the slowed accumulation on the attenuated sensory evidence relayed from the primary visual cortex in amblyopia.

The non-decision time in the amblyopic group was found longer compared to the normal group. The non-decision component includes early encoding process and late response execution process before and after the decision process, respectively.[23,44,56,57] Weindel, et al.[58] suggested that non-decision times reflect cognitively richer processes than is usually assumed. It has been shown that even a simple visual task in the laboratory settings involves not only sensory cortex, but also downstream processes that outside the sensory cortex.[59,60] Given that *Ter*s in both AE and FE were found to be increased, we speculate that the prolonged *Ter* is more likely reflecting the deficits in the post-sensory processes that are outside V1 in amblyopia. Our speculation agrees with the result from other amblyopia studies in

Investigative Ophthalmology & Visual Science

manual response time[61] and in saccadic delay.[21,62] People have also suggested that amblyopia impaired attention[12,63] and may impact cortical connections to higher brain areas, including parietal and frontal cortices.[18] However, whether the prolonged non-decision time is specific to the grating task or is a general characteristic of all visual tasks in amblyopia is an interesting question and remains to be answered.

In summary, both sensory and post-sensory factors contributed to the delayed RT in amblyopia. The effect of the sensory deficit in the primary visual cortex on RT can be compensated by increasing the stimuli contrast. The post-sensory delay provided the evidence for higher-level deficits in amblyopia.

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