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Relationships Between the VL and Reaction Time Models

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Abstract

The VL concept is based on measurements of accuracy thresholds where response times are essentially unlimited. Rea has produced a model based on reaction times, which include response times. Analysis of phenomena such as the Pulfrich illusion suggest that there is a delay time between signal and recognition that depends upon the adaptation luminance. This suggests an analysis of reaction times in terms of a simple sum of a signal strength (VL) term plus response term(s). A comparison of Rea's reaction time and this additive VL model showed that the models are similar, but that the VL model fits the data better and has a more consistent theoretical foundation.

The luminance-dependent response term appears to be needed to fit performance on the numerical verification task developed by Rea, but not the word chart reading task developed by Bailey. The above additive model suggests that the difference may depend on whether the task is processed serially and includes the delay time, or is processed in parallel and does not.

Introduction

In a previous paper, Clear and Berman showed that Rea's numerical verification (NVE) data could be fit by a model consisting of the sum of a luminance-dependent term and a visibility level (VL) term.[1,2] This model explicitly treats accuracy and speed as co-varying variables. In 1993, Clear and Berman fit both their model and Rea and Ouellette's 1991 relative visual performance (RVP) model to word chart reading speed data measured by Bailey.[3,4] The additive VL model gave the best fits, but surprisingly the "luminance"-dependent term was simply constant.

Rea has noted that most visual performance data show an increase in the maximum suprathreshold level with increases in adaptation luminance. The additive VL model has a signal strength (VL) term and a response term. In this paper I develop a hypothesis for why the response term has a luminance dependence for the numerical verification and reaction tasks, but apparently not the Bailey reading task. A model with response term that includes both a size and luminance dependence was fit to Rea and Ouellette's reaction time data.[5] The model has the same overall functional form as Rea's reaction time model, but the individual terms are very different. The explicit accuracy criteria in the VL model results in fits that are simpler and fit the data better than the reaction model. The VL model also has the advantage that many of its parameters have direct physical meanings and values that have been confirmed by independent experiments.

Rea and Ouellette's 1991 RVP model showed that the reaction time data and the NVE data are closely related. However, the theoretical justification for the RVP form is not correct, and as shown in a previous paper it does not predict the Bailey reading data well. A simple, logical adjustment of the parameters of the VL fit of the reaction data produces a better fit to the NVE data than the RVP model.

The existence of essentially independent terms in the VL model suggests that extrapolation of any given set of results to different tasks is trickier than has been recognized. Indeed, the model suggests that, under the appropriate conditions, glare may decrease reaction times. This unexpected prediction highlights the difference between visibility and suprathreshold visual performance.

Background: The Models

The first two Rea models share the same basic form for visual performance (VP = speed):

$$VP = VP_{max} \times \Delta C^n / [\Delta C^n + K^n] \qquad (1)$$

Here VP_{max} is a function of luminance, ΔC is the physical contrast C_p minus a threshold contrast C_t, n is the exponent, and K is the half-saturation function. In the numerical verification experiment, Rea only examined one size of task, so C_t, n, and K are functions of luminance. In the reaction time model, C_t and K are generalized to be functions of luminance and size, while n is actually simplified to be a constant (= 0.97). In the numerical verification (NVE) model, C_t is defined as the threshold of zero performance on the proofing task, while the reaction model used a 50% detection level for a three second exposure. This later definition is very closely related to the definition Blackwell used in deriving the VL concept.

Although the two models share the same basic form, they predict very different absolute performance levels. Rea and Ouellette assumed that this was due to differences in the simple reaction and proofing tasks. They further assumed that, although the absolute levels differ, there should be a simple linear relationship between the RVPs. In their 1991 paper, they developed a suite of three linked models to generalize the reaction time model to the NVE task and its conditions. The models are:

1) A model for the effect of age on effective luminance and contrast at the eye.

2) A model for the variation of pupil size with luminance. The NVE experiment was performed with natural pupils, while the reaction time experiment used artificial pupils.

3) The RVP model:

$$RVP = A[1 - B/VP] = A[1 - B([\Delta C_n + K_n]/\{VP_{max} \times \Delta C_n\})] \qquad (2)$$

where A = 1.4198, B = 0.0009047, and the remaining terms are from the reaction time model.

The two experimental conditions differ from each other and from the normal work environments, so a number of assumptions must be made in order to use Equation 2 to model general visual performance. The first is that visual performance depends solely on retinal illuminance (luminance times pupil area) and not luminance per se. This is why a pupil area model is needed. In the reaction experiment, subjects viewed the target monocularly (one eye occluded), while in the NVE experiment, and in normal work, viewing is binocular. The second assumption is that the transformation in Equation 2 accounts for any differences between monocular and binocular view. Both the NVE and reaction experiments apparently had a dark surround, while normal work has a fairly uniform background and surround. The third assumption is that the surround makes no significant difference. In both experiments accuracy co-varies with speed. The fourth assumption is that this co-variance is fixed, or at least does not vary significantly in terms of its effects on speed. Finally, note that the measure of size in the reaction experiment is total target area. Rea and Ouellette assume that the equivalent measure for text is the print area of a single character. Equation 2 is limited to relatively large sizes where resolution is not a problem.

The additive VL model fit reading time, T, which is the inverse of speed:

$$T = T_{NV} + T_c /[(F \times VL/V) - 1] \qquad (3)$$

Here T_{NV} is the non-visibility time (cognition and processing times), T_c is a time constant that is related to how VL changes with exposure time, F is the function, $F = (t + T_c)/t$, relating VL as measured with a stimulus exposure time t to VL with infinite exposure time, and V is the visibility level corresponding to the accuracy criteria used by the subject. Equation 3 was derived by noting that threshold detection contrasts vary as a simple rational fraction of exposure time, with T_c being the time constant. Inverting this relationship gives times as a function of accuracy, as above. In the original paper, V was fit to the measured accuracy on Rea's NVE experiment, T_c was taken to be a function of luminance and size as described by Enzmann (as quoted by Adrian), and T_{NV} was found to vary slightly as a function of luminance.[6,7] Enzmann's function was meant to be a refinement on the work done by Blondel, where T_c was approximated as having a fixed value of 210 msec. Our fit had an error in the calculation of T_c, so the values for the constants are not optimal. In the 1993 paper T_c was fixed at 210 msec, T_{NV} was fit as a constant, and V was fit as a two-term rational fraction of VL, as there was no accuracy data. This simple fit was markedly better than the RVP model in fitting the Bailey data.

Equivalence of the Functional Forms of the Additive VL and Reaction Time Models

Rea and Ouellette's model, as given in Equation 1, is in terms of speeds. Inverting it gives a two-term equation in time. Noting that ΔC can be written as $C_t \times (C_p/C_t - 1) = C_t \times (VL - 1)$, we get an equation which is almost identical in form to the additive VL model:

$$1/VP = T = 1/VP_{max} + [(K/C_t)^n/VP_{max}]/[VL - 1]^n \equiv t_{NV} + t_c /[(F \times VL/v) - 1]^n \qquad (4)$$

The rightmost portion of Equation 4 was written with lower case letters as a reminder that although Equations 3 and 4 share the same factors, the expressions for the factors differ. The only difference in overall form between the reaction model and the additive VL model is that the former has an exponent n = 0.97, while the latter has an exponent of 1. The non-unary exponent is equivalent to assuming a power law for the variation of threshold contrast with exposure time, t:

$$C_t = C_\infty \times [t^{1/n} + T_c{}^{1/n}]/t^{1/n} \qquad (5)$$

Here C_∞ is the threshold contrast for infinite viewing time. Blondel's derivation of this expression is pre-computer, and it is unlikely that he even attempted to distinguish between an exponent of 1 and 0.97. Thus, it appears that the difference in n is at most a difference in curve fitting, and not a basic difference in theory.

Values of the Factors of the Reaction Time Model

In the additive VL model, the different factors—T_{NV}, T_c, F, and V—have specific physical meanings and a correspondingly limited range of acceptable values. These factors in the reaction model were not constrained in the same manner, and their values are very different from those of the VL model. No accuracy criterion, V, was used in the derivation of the reaction model, and the re-expression of the model in the VL form shows that this leads to an inconsistency in the model, which is clearly visible in a plot of the residuals and in the values of the other derived parameters.

In Equation 4, v = F (their ratio is 1). In the reaction experiment threshold presumably occurs at or near the longest duration available to the subject, which is 3 seconds. This means F and v will be slightly above 1 (1.07 with Blondel's estimate of T_C = 210 msec; less with Enzmann's estimates). For the parameter V, a value of 1 represents threshold conditions, while a value of 2 represent accuracies on the order of 95% or above. This means that the reaction model predicts zero performance near threshold, although there has to be a non-zero performance at threshold in order for it to be measured. This inconsistency in the model is shown for the reaction speed data in Figure 1 (the reaction data were provided by Rea and Ouellette). Ideally the points should cluster near zero. The vertical axis was plotted in terms of percent error (100 x [prediction - measurement] / measurement), as a value of -100% unambiguously represents a point where the model incorrectly predicts that performance should be zero. Figure 1 shows that this occurs near VL = 1 (threshold) and that it further leads to underestimates of performance up to a VL of about 1.5. The remainder of the fit appears good, although there is a slight overestimate of the slope for VLs up to about 50 and an error (equivalent to an overestimate of about 10 msec) for VLs greater than 100. The latter are points with positive contrasts of 10 or so, and the error may be due to the influence of the extremely bright target on T_{nv}. Figure 2 shows that the inconsistency in the treatment of accuracy affects the fit for points below about 1/3 the maximum speed. In this plot the vertical axis is an unweighted residual ([prediction - measurement]/constant). Figure 2 also shows the mild dip in the residuals at about half maximum speed due to the error in slopes observed in Figure 1, but otherwise shows a reasonable pattern above the threshold failure zone.

At high VL values, the contribution of the signal strength term is dependent upon the ratio of T_C x V/VL. If V is estimated small, then T_C has to be large to compensate and give good fits. Over the conditions of the reaction time experiment, the reaction fit estimates for T_C range from 350 to over 700 msec. By comparison, Blondel's estimate was 210 msec, while Enzmann predicts values from 80 to 170 msec (Enzmann's functions match Blondel's estimate only at low luminances and sizes.) The discrepancy between the reaction fit values and the independently measured values is further evidence that an accuracy criteria needs to be part of the model.

In the reaction model T_{nv} varies by 70 msec over the range of luminances studied. This is about twice what would be expected if this term was solely due to the delay times that have been measured for the Pulfrich illusion (see below).[8] However, the fit to this term is not independent of the fit of the signal strength term, so this discrepancy may be just another reflection of the inconsistency in the treatment of accuracy in the later term.

Additive VL Model

The VL concept was originally developed to explain accuracy of response when the time to make the response was not part of the performance measure. Clear and Berman showed how to predict a signal detection time from the VL term, and then produced a more general performance model by adding a response time. However, they did not attempt to produce a sophisticated model for the response term, and instead either fit it as a constant or, in the case of the NVE data, simply used four slightly different values for the four luminance conditions studied.

Clear and Berman suggested that the small luminance dependence found in the NVE data was due to the scanning of the eye over the numbers, but this seems inconsistent with the fact that no obvious luminance dependence was found for the Bailey data. In discussion of this issue, Rea has suggested that the luminance dependence may be related to the Pulfrich phenomena. As is shown below, this latter hypothesis can be made consistent with both sets of data.

The Pulfrich illusion is that an object moving transversely appears displaced either forward or backwards of its actual trajectory when viewed binocularly, but with one eye having a neutral density filter in front of it.[8] The explanation for this illusion is that the time delay from the retina to the brain depends upon the illumination on the eye. The eye with the filter sees the object at a later time (earlier location on its trajectory), so the fused binocular image is displaced forward or backward from the actual trajectory.

In the reaction task this luminance-dependent delay time clearly must be added to the total response time. However, the fastest way to read is to anticipate word recognition and make the saccade early. A fast reader may finish visually scanning a passage substantially in advance of his comprehension of the passage. In this scenario there is an initial delay at the start of reading, but no further delays during the actual reading. The delay time is thus averaged over the entire passage (see Figure 3). Partial confirmation of this idea comes from some of our faster subjects on a task/instruction experiment, who commented that they sometimes had to go back up the list to mark an error, indicating that they had visually scanned far beyond the number that they were mentally reviewing.

Initially I tried VL model fits with the same form for T_{nv} as was used by Rea and Ouellette. However, the residuals from these fits showed a clear size dependence, so the fits shown in Figures 4 and 5 are based on the expression $T_{nv} = C - D \ln(\text{luminance}) - E \ln(\text{size})$, where C, D, and E are fitted parameters. Although the size dependence was a surprise, it was not completely unprecedented, as Clear and Berman found unexpected and surprisingly strong size effects in their analysis of the Bailey reading experiment. A cognitive basis for the size term seems not unreasonable, but is at this time just speculation. The luminance-dependent portion of T_{nv} varies over a range of about 30 msec for the conditions of the experiment, which is about the value expected from fits to the Pulfrich data.

In the Bailey reading experiment, subjects simply gave up when visibility was too low, and a simple two term rational fraction fit of V versus VL gave excellent fits. Subjects in the reaction experiment did not give up at low visibilities. This is equivalent to assuming that F x VL/V goes to a value slightly greater than one as VL approaches zero. The geometric mean function (Equation 6) was used to fit the accuracy constraints:

$$F \times VL/V = [A^n + (VL/B)^n]^{1/n} \qquad (6)$$

Here A, B, and n are fitted constants, with A being the lower limit for the expression as VL approaches 0, and B being the upper limit for V/F as VL becomes large. The parameter values represent a particular pattern of accuracy criteria, and it is expected that different instructions or experimental conditions (such as in the Bailey reading experiment where people give up as VL becomes small) will give different values.

Blondel's value for T_c (210 msec) gives moderately good fits, but unrealistic values of the constants A and B. As noted earlier, the best-fitted values of V and T_c are related. Fits with T_c as a free variable, or with T_c given by Enzmann's equations (which straddle the value best fitted constant value), give realistic values of A and B and a substantially lower error (mean sum of squares) than the reaction fit (see Table 1). Adrian's extrapolation of the Enzmann equations above 50 minutes of arc seems to have resulted in a slight overestimate of T_c for these sizes, but, as Figure 4 shows, the very strong bias error shown in Figure 1 is eliminated by the adoption of a variable accuracy criterion (V). In viewing this figure it is important to note that the percent error representation gives a distorted view of positive errors, as they are potentially unbounded, while negative errors can never be greater than

100%. The percent error approach also inflates the significance of errors where performance is low. The errors were plotted against percent error to provide a comparison to Figure 1.

Figure 5 shows that the additive VL fit gives an unbiased fit over almost its entire range. The additive VL interpretation not only leads to better fits, it does it with little or no added complexity. The reaction fit has 11 fitted parameters and has a very complex expression for T_C. The fixed T_C variant of the VL model has only seven free parameters and is much simpler in form. Enzmann's functions make the VL model more complex than the reaction model, but actually reduces the number of free parameters to 6. The VL interpretation also has the advantage of being consistent with threshold experiments and of having a number of "free" parameters (A, B, D, and T_{nv}) that have explicit physical interpretations, with fitted values that are consistent with the values determined in completely independent experiments.

Generalizing the Reaction Fits: The NVE Data

For practical purposes, the reaction task is important only to the extent that the models of it can be generalized to other tasks. Rea and Ouellette derived the RVP model to generalize the reaction time results, and validated it against the numerical verification experiment (NVE) results. Table 1 shows the mean sum of squares for the NVE and RVP fits over the range of luminances measured in the reaction experiment (12 to 41 cd/m^2). The overall level of accuracy of both fits is about ±10%, which is quite good, but the NVE fit is significantly better at the 5% significance level ($F(7,39) = 2.85$). The RVP fit shows a slight trend in its residuals that is not present in the NVE fit.

Although the RVP model fits the NVE data fairly well, it is much less successful with the Bailey data. The mean sum of squares of the residuals of the RVP fit to the average subject data was five times larger than that of an additive VL model. A more careful analysis of the theory and data shows that a straight-forward generalization of the additive VL model is better both theoretically and in terms of the degree of fit.

The original justification for the RVP model was that it represented a linear transformation of one metric into another, such as is done between temperature scales such as Celsius and Fahrenheit. However, RVP is the ratio of the speed to do a task under given conditions of size, luminance, and contrast, to the speed under reference conditions of size, luminance, and contrast. Multiplying Equation 2 by the reference speed gives a linear equation of speed versus time (inverse speed). This is an inverse linear equation. It does not represent a simple linear transformation of one metric to another, and does not have a simple theoretical justification.

In the VL approach, fitting one set of results as a function of another requires, as a minimum, that the threshold contrasts be either equal or proportional to each other. The reaction time threshold contrasts average approximately 0.6 times the NVE threshold contrasts, with only about 1% scatter. We also have to assume that both sets of data either include the luminance-dependent term (which appears true in the present case) or exclude it. Given these two preconditions, the only factors that can vary are the constant portion of the cognition time (C) and the accuracy criteria (A, B, and n of Equation 6). To keep the comparison on an equal footing with the two-parameter RVP fit, I left n alone and fixed C as being C from the VL fit to the reaction time data plus the minimum time from the NVE fit, and minus the minimum time estimated by the VL fit. The parameter values and degree of fit are shown in Table 1. The VL fit is not significantly different from the NVE fit ($F(7,39) = 1.2$) and shows no major trends in the residuals.

Again consider the RVP fit. To get a good fit requires the right limits (the minimum and maximum performance levels) and the right slope versus VL. For the single size and narrow luminance range of the NVE task, the two coefficients of the RVP fit can be adjusted to give the right limits. The threshold contrasts are proportional, so the VLs are too. The slope of the VL fit depends upon the minimum time to do the task and the accuracy criteria, while the RVP slope depends upon the two free parameters. For the NVE experiment, the slopes of the two models are close, but this is due to the original overestimate of the slope by the reaction fit (see Figures 1 and 2), the value of the minimum time to do the NVE task, and the time on the reaction task that corresponds to zero performance on the NVE task. The Bailey task had a wider range of sizes and luminances, which made the limit estimates poorer, and a different set of times, which made the slope estimate poorer. The RVP fit suffered accordingly. Basically, the form of the RVP fit assures a fairly good fit to the limits. However, it is simply an empirical fit. Whether it has approximately the right slope, and thus fits the data well, depends upon the task and appears at this time to be a matter of chance.

Discussion

The attraction of the RVP model is Rea and Ouellette's suggestion that it is a general measure of visual performance applicable to a wide range of tasks. Unfortunately, this does not appear to be true. The VL analysis indicates that there are a number of factors that determine performance, and that these factors will have different weights for different tasks. More information is needed about the importance of the different factors, and in a number of cases more information is needed about the factors themselves.

For example, all the VL fits in this paper were based on Rea's threshold contrast formula. This is not the only available formula, and in fact Clear and Berman used a formula based on the Blackwell-Taylor data in their VL model fit of the Bailey data.[3] The latter threshold fit is more sensitive to luminance and size than the Rea fit, and, as shown in Figure 6, can differ from it by a factor of two. Both experiments are based on detection of a simple task (squares or disks), so the difference is disturbing. The reaction task was performed monocularly, using an artificial pupil, and with target and background embedded in a dark surround, while the Blackwell experiment involved binocular vision with natural pupils and an extended, almost uniform background and surround. Threshold contrasts in the NVE experiment match the reaction threshold data more closely than the Blackwell data. The NVE experiment was performed in a dark room, with subjects who used binocular viewing and natural pupils. From this description it appears that surround conditions are probably important in determining the shape of the threshold contrast curves. This issue needs to be further researched, and resolved. In the interim, it seems more reasonable to use the Blackwell data than the Rea and Ouellette data, as the former were taken under conditions closer to those of normal visual work.

To utilize the simple disk or square data for letters or numbers, Rea and Ouellette recommended using the printed (inked) area of a single letter or number, while Blackwell recommended using a "critical detail" size, which Clear and Berman have interpreted as being 1/5 the symbol height. For the fonts that Rea and Ouellette used, the print area is equivalent in lineal dimension to about 2/5 the symbol height, or twice what is used by Clear and Berman. The NVE data is consistent with Rea and Ouellette's recommendation. The best estimate is probably both font-dependent and task-dependent, and needs to be further researched.

I have already noted that the luminance dependent term of the VL model (D) may not be present, or may be very small, in tasks such as reading. Another important point is that this term should not respond to disability glare in the normal manner. Disability glare approximately follows a $1/\Theta^2$ law. It has been shown to be caused by light scatter in the eye and is thus present even if the glare source is focused on the blind spot of the eye. It has been found that, for the Pulfrich phenomena, a glare source can reverse the illusion, but not if it is focused on the blind spot.[9] Thus the response of the delay time term, D ln(L), to glare is presumably due to neuronal interactions, and not scatter. The delay time term should therefore be proportional to retinal illuminance (Trolands) and will respond to a glare source as cos(Θ). If this hypothesis is correct, it should be possible to slightly improve performance as measured by reaction speeds by introducing some off-axis glare.

Berman et al. have shown that the scotopic content of surround lighting affects pupil size and accuracy near threshold.[10,11] It is unclear at present whether the effect on accuracy is only present near threshold, as has been claimed by Rea. At present these accuracy effects are not included in the additive VL model.

Rea and Ouellette have included a simple model for pupil size as part of the overall RVP model. Their pupil size model does not include information from Berman's work on scotopic lighting.[12,13] A simple fit of the Berman work that also works well with other data on pupil size is given in an appendix to this paper. The appendix also reproduces Enzmann's T_C function, and a Luminance as a function of Trolands fit.

Rea and Ouellette's age effect model is substantially different from that developed by either Blackwell or Adrian.[14,15] The Rea estimates are based on fits to one of Rea's early visual performance models and appear as if they may be sensitive to inaccuracies of the modeling. Blackwell and Adrian's estimates are based on more direct measures of the postulated effects and should thus be more reliable.

Conclusion

The original Rea and Ouellette models were based on the concept of using the same functional form for the psychophysical response (speed) as has been found for the electrophysiological response. Our analysis has shown two problems with this approach. The first is that their guess as to what constitutes a signal appears to be too limiting (VL versus F x VL/V). The second is that this approach ignores the fact that there appears to be more than one step in the processing of the visual information.

An approach based on an additive model of times—a delay time, a cognitive time (including a size dependent term), and signal strength (VL) term—yields a model with the same overall form, but with simpler terms, a better fit to the speed data, and an explicit inclusion of an accuracy prediction (or fit). Many of the constants in this model have direct physical meaning and have values that have been independently verified in other experiments.

Rea and Ouellette have proposed a simple RVP model as predictive of visual work for a wide class of tasks. The analysis in support of the additive VL model suggests that this is an oversimplification. The VL model does appear to provide a good framework for modeling speed, but different tasks cannot be expected to share the same parameter values as the reaction or NVE tasks.

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APPENDIX: SUPPLEMENTARY EQUATIONS

Enzmann's equations for T_C:

$T_C = [K(S)^2 + K(L)^2]^{1/2}/2.1$, where S is the size in minutes, L the luminance in cd/m^2, and

$K(S) = 0.36 - 0.0972 \times T(S)/[(T(S) - 2.513) \times T(S) + 2.7895]$, $T(S) = \log10(S) + 0.523$, and

$K(L) = 0.355 - 0.1217 \times T(L)/[(T(L) - 10.4) \times T(L) + 52.28]$, $T(L) = \log10(L) + 6$.

For $S \leq 0.3$, $K(S) = 0.36$. For $S \geq 50$, $K(S) = 0.136$.

For $L \leq 0.000001$, $K(L) = 0.355$. For $L \geq 10{,}000$, $K(L) = 0.1$.

Pupil area, A, (mm^2):

$A = 3 + 47/[1 + 2.449 \times PL]^{.45}$, where PL is a pupil lumen and is defined as:

PL = Photopic lumens x (0.26 + 0.74 x S/P), where S/P is the scotopic/photopic lumen ratio

Luminance(Trolands) - this was used to determine Enzmann's T_C values as a function of Trolands (T):

$L(T) = T/[3 + 47/(1 + C \times T)^n]$, where C and n are functions of the S/P ratio:

$C = 0.01175 + 0.03737 \times S/P$, and

$n = 0.69098 + S/P \times (0.00284 \times S/P - 0.01321)$.

Enzmann's fits were in part based on Blackwell's data, so a value of S/P = 1.41 (incandescent lamp) was assumed.

Table 1: Parameters and degree of fit - reaction and NVE experiments

	Reaction data VL fits		Rea-Ouellette fit	Numerical Verification Data		
	Simple Tc	Enzmann's Tc	Reaction fit	NVE fit	RVP	VL fit
Mean sum of square error (smaller is better)	0.084	0.079	0.135	0.0047	0.0071	0.0057
Parameter						
Critical Time	118.2	note 1	N.A.	N.A.	N.A.	note 1
Response terms						
C: constant	407.8	389.2	N.A.	N.A.	N.A.	note 2
D: Luminance dependence	-5.460	-3.209	N.A.	N.A.	N.A.	-3.209
E: Size dependence	-15.405	-12.117	N.A.	N.A.	N.A.	-12.12
Accuracy Criteria terms						
A: lower limit - FVL/V	1.048	1.056	N.A.	N.A.	N.A.	0.9602
B: upper limit - V	1.872	1.953	N.A.	N.A.	N.A.	2.439
n: shape constant	3.1427	3.3026	N.A.	N.A.	N.A.	3.3026

note 1: Derived from Enzmann's formulas: varies from 85 to 170 msec in Reaction experiment and 111 to 115 msec in NVE experiment.

note 2: Set equal to C from the reaction fit plus the difference between Rea's estimated minimum time and the VL estimated minimum time: = 699 msec.

Figure 1: Percent error versus VL - Reaction fit

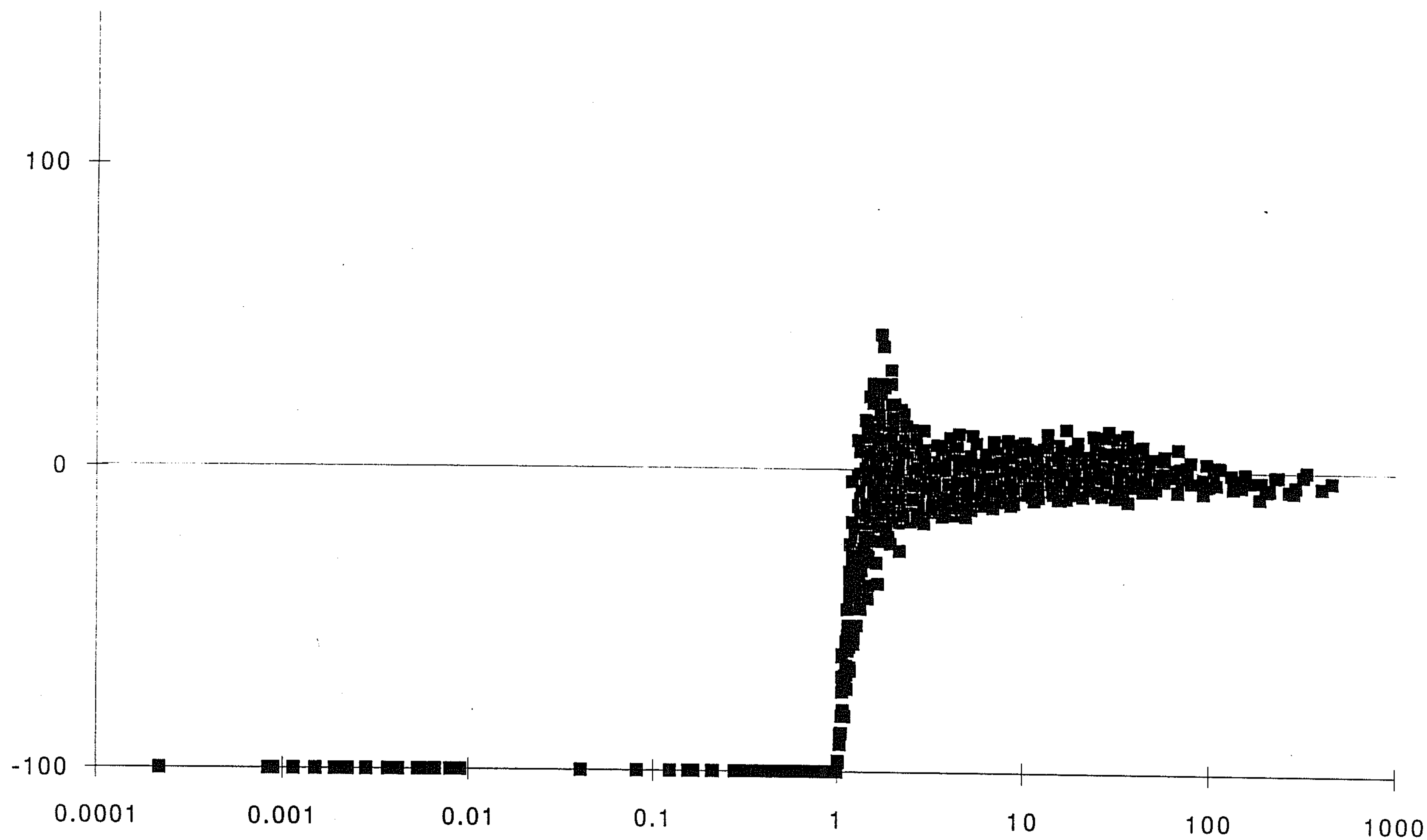


Figure 2: Reaction fit - Residuals versus fitted speed

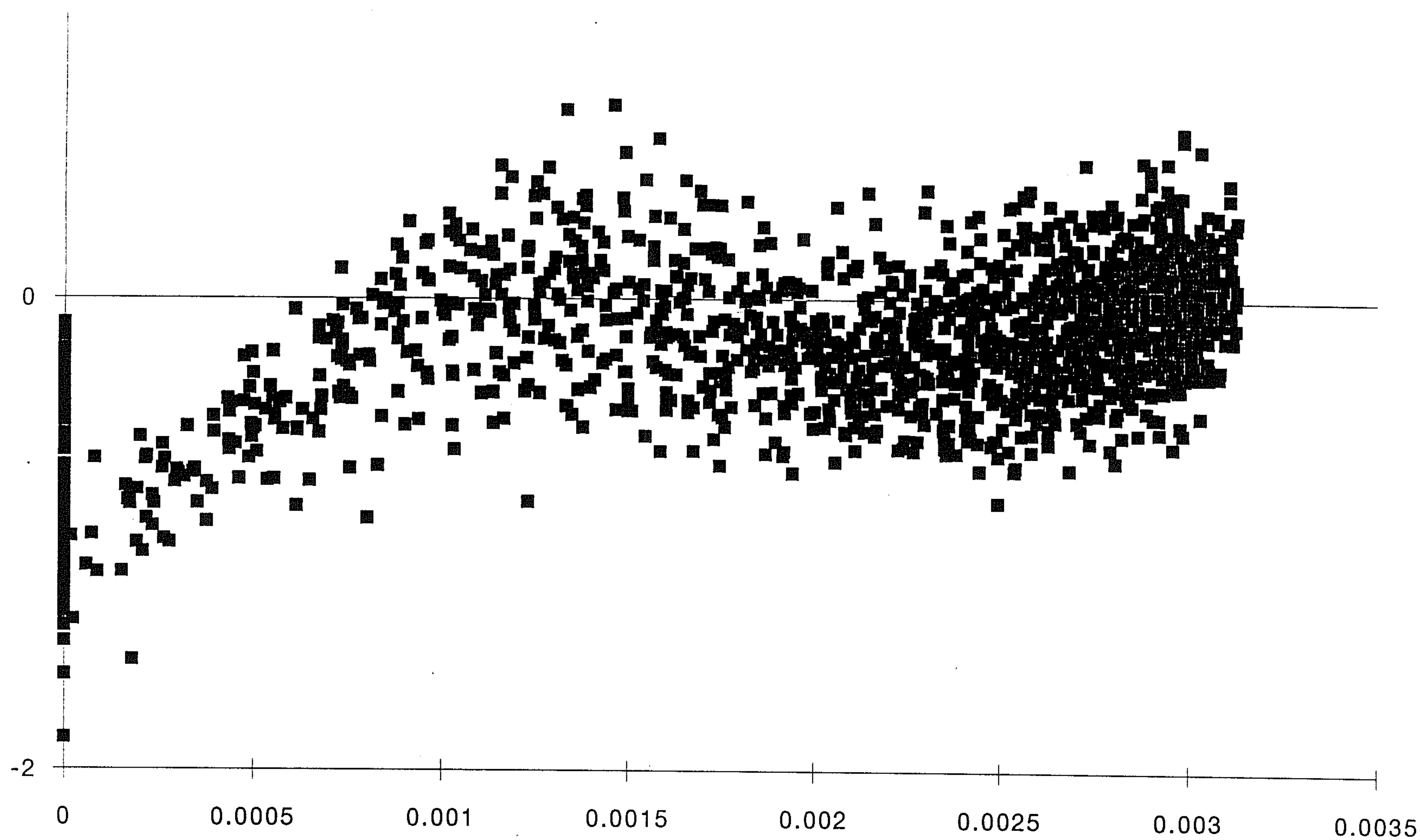
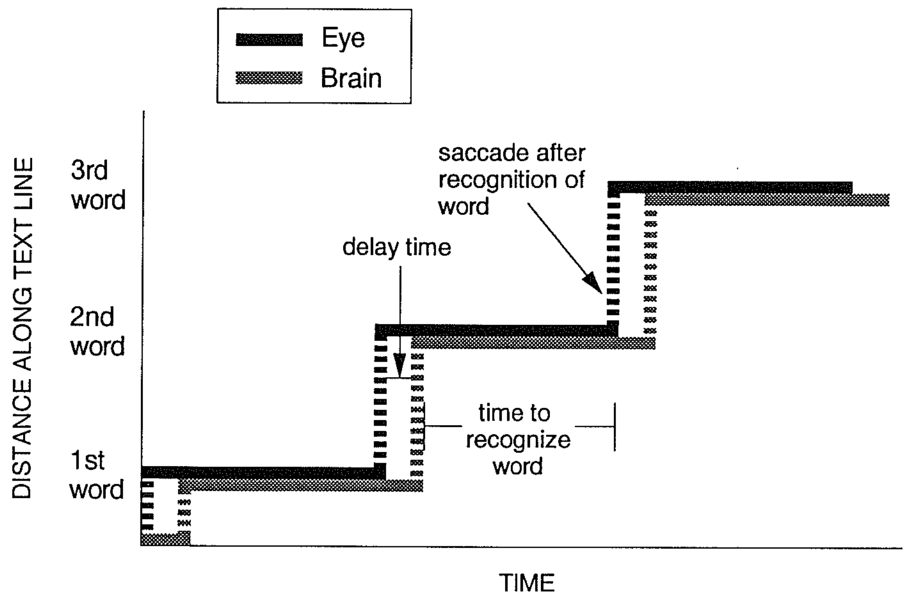
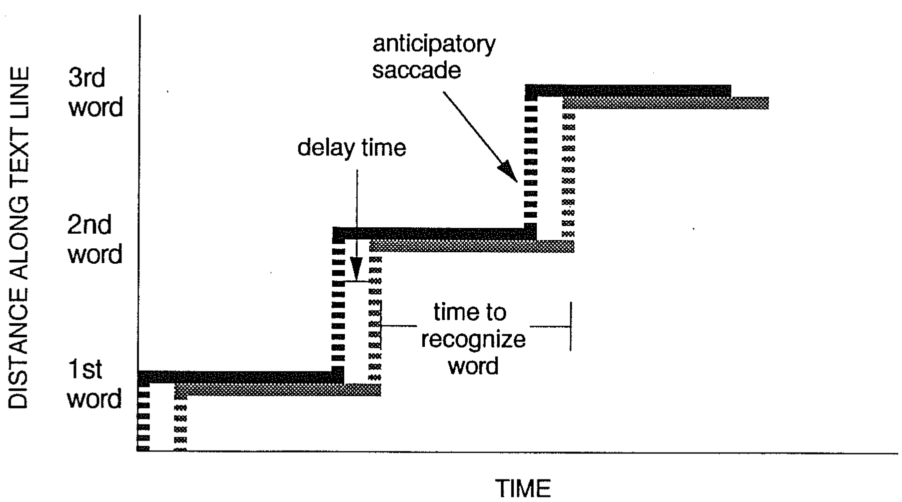


Figure 3: The Influence of a Delay Time on Slow and Fast Reading.

The slow reading case is equivalent to the reaction time experiment as subjects must know they have seen the task before proceeding.



Slow Reading



Fast Reading

Figure 4: Percent error versus VL - Additive VL fit

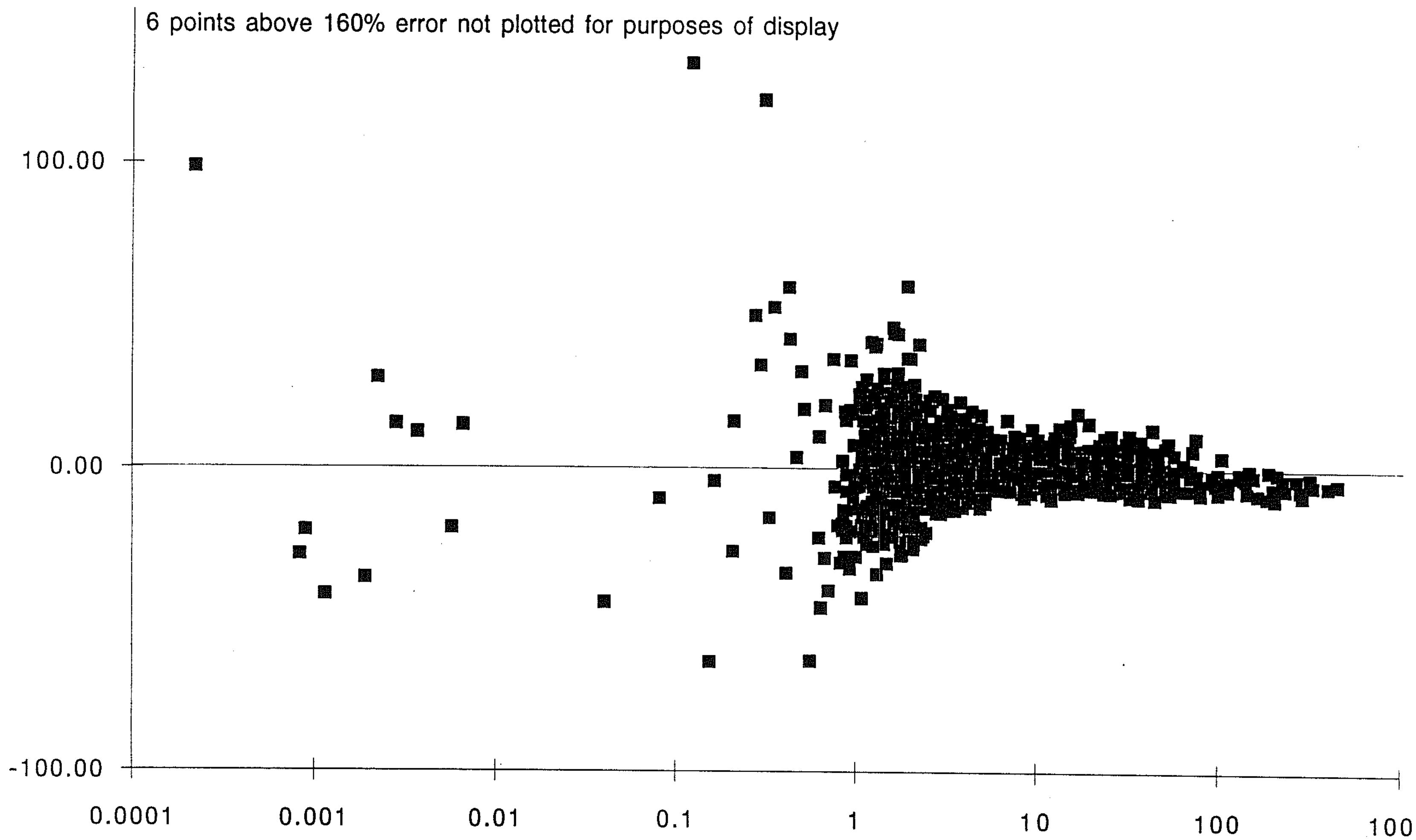


Figure 5: Additive VL fit: Residuals versus fitted speed

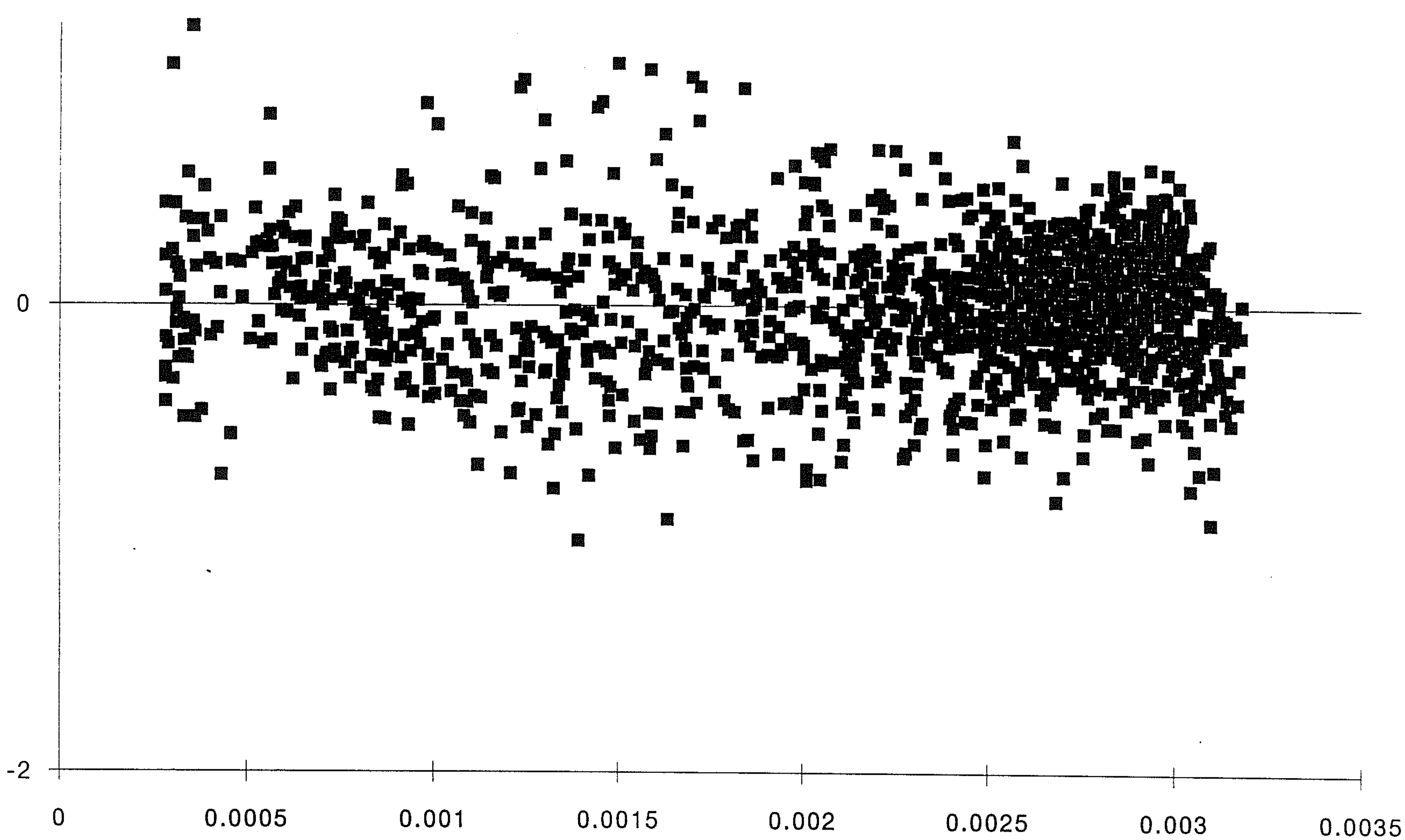


Figure 6: Threshold contrast ratios: Reaction time data/Blackwell-Taylor data