ARE VERY LARGE EXPERIMENTS NECESSARY?
A RE-ANALYSIS OF GEAR & PINION DATA

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ABSTRACT

Fractional factorial designs provide an efficient method of conducting industrial experiments. Taguchi's "product array" approach (Taguchi 1987) is a special case of these designs which has proven effective in improving the robustness of product and process designs to manufacturing and environmental variations. Taguchi's product array consists of a control array completely crossed with a noise array. In some applications, however, this method for introducing noise in parameter design experiments leads to unnecessarily large and expensive experiments.

Instead a single array can be used for both control and noise factors. This "combined array" approach is more flexible and will often allow the size of the experiment to be reduced dramatically. This report uses real data to demonstrate how a smaller combined array design will often lead to essentially the same conclusions as a much larger product array.

1 Introduction

A project to investigate the geometric distortion of drive pinions and gears during a heat treatment process was performed at an axle plant. This project was very successful in identifying operating conditions which significantly improve the quality of the parts being produced; however, a relatively large number of runs were performed, thus making the experiment very long and expensive. The purpose of this study is to determine whether similar results could have been obtained using a smaller number of runs. The results, we hope, will help guide the design of future experiments.

2 The Original Experiment

The original experiment involved two sizes (7.5 inch and 8.5 inch), and several types of gears and pinions. The primary measures of distortion were: stem runout (for the pinions), and dish, kink o.d., and kink i.d. (for the gears). The experiment included five control factors and three noise factors. These factors were;

Control Factors:

A	Carbon Potential
B	Operating Mode
C	Last Zone Temperature
D	Quench Oil Temperature
E	Quench Oil Agitation

Noise Factors:

F	Furnace Track
G	Tooth Size
H	Part Positioning

An explanation of the levels used for these factors is given on page 14. Factor H (part position), though initially labelled as a noise factor, was treated as a control factor in the analysis since the orientation of the part in the furnace can be easily adjusted.

The control array used was a 16 run, resolution V, fractional factorial design [FF$(16, 2^{5-1})$] with the defining relation I=ABCDE. The noise array used was a full factorial 2^3 design. Two replicates were performed for each combination of settings; thus 256 runs were required for each type of gear and pinion included in the experiment. The data obtained was analyzed in three ways:

1. Raw data analysis; raw data used as the response.
2. Nominal; used $z = -10\log(s^2)$ as the response.
3. Smaller-The-Better; used $z = -10\log(\frac{1}{n}\sum y_i^2)$ as the response.

The three analyses were given equal weight, in choosing the optimum operating conditions. These conditions were identified for overall performance with respect to the different parts and the various measures of distortion. The recommended conditions were as follows:

A (Carbon Potential)	level 1
B (Operating Mode)	level 2 for stem runout despite a negative effect on dishing.
C (Last Zone Temperature)	level 1 due to strong interaction with A and advantages for 7.5 inch parts.
D (Quench Oil Temperature)	intermediate setting (1.3)

	since low level was better for stem runout,
	but bad for kinking.
E (Quench Oil Agitation)	level 1
	even though it showed an interaction with D.
H (part position)	level 1
	was extremely important for dishing.

3 Purpose

The objective of this study was to determine whether a smaller experiment would have yielded essentially the same recommendations as the original experiment. To accomplish this, selected fractions of the experiment were analysed for dishing, kink i.d., and kink o.d. using the 7.5 inch gear data (parts 161 & 950). The raw data analysis was performed on the following fractions of the experiment:

1. Analysis of the full data set. This analysis uses the total information collected during the experiment; therefore, it is used as a benchmark with which to compare the results for the various fractions. The original experiment used an inner array/outer array design. The re-analysis was based on the combined array. This means that no distinction was made between control and noise factors in the actual analysis. This was necessary due to the restrictions imposed by fractionating the original design.

2. Analysis of the half defined by I=E and I=-E. Each half has 128 runs. This split was used since factor E was relatively unimportant in the full analysis. The results from the two halves are compared to each other as well as to the results from the full analysis.

3. Analysis of the half defined by I=ABFGH and I=-ABFGH. Each half has 128 runs. Since the original experiment used the defining relation I=ABCDE, the two halves have defining relations I=ABCDE=ABFGH=CDEFGH and I=ABCDE=-ABFGH=-CDEFGH respectively. Both halves have resolution V (that is, main effects and 2 factor interactions are estimable if 3 and higher factor interactions are negligible.). Again the results are viewed for consistency between the two fractions as well as compared to the full analysis.

4. Analysis of the two halves of the experiment defined by I=ADGH and I=-ADGH, and of the four quarters defined by I=±ADGH=±ABFG. The defining relations for the halves are:

   I=ADGH=ABCDE=BCEGH

   I=-ADGH=ABCDE=-BCEGH

   Each half has 128 runs. The defining relations for the quarters are:

   I=ADGH=ABFG=ABCDE=BDFH=BCEGH=CDEFG=ACEFH

   I=ADGH=-ABFG=ABCDE=-BDFH=BCEGH=-CDEFG=-ACEFH

   I=-ADGH=ABFG=ABCDE=-BDFH=-BCEGH=CDEFG=-ACEFH

   I=-ADGH=-ABFG=ABCDE=BDFH=-BCEGH=-CDEFG=ACEFH

   Each quarter has only 64 runs. All of these designs have resolution IV.

Using a single array (which is called a combined array by Shoemaker, Tsui, and Wu 1989) for both the control and noise factors has two definite advantages over Taguchi's approach which calls for the use of an inner array crossed with an outer array. The former approach requires much fewer number of runs, and the combined array can be chosen in a flexible manner to accommodate the estimation of selected control-by-control and control-by-noise interactions. Detailed information can be found in the STW paper.

4 Analysis

This experiment involved re-analysing three characteristics (kink i.d., kink o.d., and dishing) for two part types (161, and 950) of the 7.5 inch gears. The six data sets are denoted by kinkid161, kinkod161, dish161, kinkid950, kinkod950, and dish950. A combined array approach was used to analyse the the following fractions of each data set:

1. Full data set.
2. Half fractions I=±E.
3. Half fractions I=±ABFGH.
4. Half fractions I=±ADGH.
5. Half fractions I=±ABFG.
6. Quarter-fractions I=±ADGH=±ABFG.

The raw data was averaged over the two replicates. Main effects and 2 factor interactions were then estimated using the combined array. Half normal plots were used to determine which effects should be considered significant. In cases where effects were marginally significant on the half normal plots, an ANOVA was performed on the questionable effects. The results were then used to classify these effects as significant, marginally significant, or not significant. Table 1 (see page 14) summarizes the effects found to be significant for the various fractions of each data set. Table 2 (see page 15) ranks the three largest effects for each analysis.

The following is a summary of the results obtained for each analysis:

1. <u>**The analysis of the complete data:**</u>

kinkid161 The half normal plot (see page 17) suggests no significant effects.

kinkid950 The half normal plot (see page 17) indicates main effects B, D, and F may be significant. To further investigate this, the remaining effects were pooled for an estimate of error, and the following ANOVA was done:

	df	SS	MS	F	p-value
B	1	272.25	272.25	5.77	0.017
D	1	162.56	162.56	3.45	0.065
F	1	144.00	144.00	3.05	0.082
Res	252	11889.18	47.18	—-	—

From this B was classified as a significant effect, and D was labelled marginally significant. The signs of the effects indicate that B should be set at level 2, and D should be set at level 1.

kinkod161 The half normal plot (see page 17) indicates that the interaction effects CF, and DF may be significant. The following ANOVA was done to further investigate these effects:

	df	SS	MS	F	p-value
CF	1	246.10	246.10	3.50	0.06
DF	1	183.94	183.94	2.62	0.11
Res	253	17777.96	70.27	—	—

Therefore, CF was classified as marginally significant. The two-way interaction plot for CF was used to choose the level of C such that the mean was small and the change over the noise variable F was small. Setting C at level 1 was the parsimonious choice.

kinkod950 The half normal plot (see page 17) suggests that the main effects B, D, and F, as well as the AH interaction may be significant. These effects were further investigated using an ANOVA:

	df	SS	MS	F	p-value
B	1	484.00	484.00	5.32	0.022
D	1	356.24	356.24	3.92	0.049
AH	1	356.24	356.24	3.92	0.049
F	1	297.56	297.56	3.27	0.072
Res	251	22835.95	90.98	—	—

B was classified as significant. D and AH were classified as marginally significant. The signs of the B, and D effects suggest setting B at level 2, and D at level 1. The two-way interaction plot for AH suggests setting both at their low levels.

dish161 The half normal plot (see page 17) strongly suggests that the H, B, and C main effects are significant. The signs indicate all three should be set at level 1.

dish950 The half normal plot (see page 17) strongly suggest that the H, and B main effects are significant, and possibly the A main effect. An ANOVA table, however, indicates that the A main effect is not significant. The effect signs suggest setting both B and H at level 1.

2. <u>**The analysis of the data split on E:**</u>

kinkid161 Half normal plots (see page 18) suggest no significant effects for either half-fraction.

kinkid950 Half normal plots (see page 18) suggest no significant effects for either half-fraction.

kinkod161 The half normal plot (see page 19) for one half-fraction suggests that the CF and BG interactions are significant. No significant effects are found for the other fraction.

kinkod950 The half normal plots (see page 19)indicate that B is marginally significant in one half-fraction and D is marginally significant in the other.

dish161 Main effects H, B, and C are strongly significant for both half-fractions (see page 20).

dish950 Main effects H, and B are strongly significant for both half-fractions (see page 20).

3. <u>**The analysis of the data split on ABFGH:**</u>

kinkid161 Half normal plots (see page 21) suggest no significant effects for either half-fraction.

kinkid950 Half normal plots (see page 21) suggest B is significant for one half-fraction. There are no significant effects in the other half-fraction.

kinkod161 The half normal plots (see page 22) suggest no significant effects for either fraction.

kinkod950 The half normal plots (see page 22) suggest no significant effects for either fraction.

dish161 Main effects H, B, and C are strongly significant for both half-fractions (see page 23).

dish950 Main effects H, and B are strongly significant for both half-fractions (see page 23).

4. **The analysis of the data split on ADGH, and ABFG:**

kinkid161 Half normal plots (see pages 24, 27, & 30) suggest no significant effects for any of the half-fractions or any of the quarter-fractions.

kinkid950 Half normal plots (see pages 24, 27, & 31) suggest B is marginally significant for one half-fraction. There are no significant effects in the other half-fraction or in any of the quarter-fractions.

kinkod161 The half normal plots (see pages 25, 28, & 32) suggest no significant effects for either of the half-fractions or for 3 of the 4 quarter-fractions. The CH interaction effect was found to be significant for the other quarter-fraction.

kinkod950 The half normal plots (see pages 25, 28, & 33) suggest that B is significant for one of the half-fractions, and marginally significant for another. No significant effects are found in the other half-fractions. The B main effect, and the AC interaction effect are found to be marginally significant in one of the quarter-fractions. No significant effects are found in the other three quarter-fractions.

dish161 Main effects H, B, and C are strongly significant for both half-fractions (see pages 26, 29, & 34), and for 3 of the 4 quarter-fractions. H, and B are found to be significant in the fourth quarter-fraction.

dish950 Main effects H and B are strongly significant for both half-fractions (see pages 26, 29, & 35), and for 3 of the 4 quarter-fractions. H was found to be significant on the fourth quarter-fraction.

5 Summary

On examination, Table 1 (see page 14) shows a large degree of consistency in the factors judged important with respect to dishing. For the dish161 data, H, B, and C are judged significant in the full analysis. These three main effects are found to be significant for all fractions except one quarter fraction where only H and B are significant. For the dish950 data, H and B are judged significant in the full analysis. Again these two main effects are found significant in all fractions except one of the quarter fractions where H appears alone. The results for the kink data sets are not quite as clear cut, but still show a great deal of consistency in the ranking of effects according to importance. It is not unexpected that the results for kink are not as clear cut, since the effects found to be significant in the full analysis are not as dramatically significant as with the dish data. In the analysis of the full data sets only the B main effect is deemed to be significant (only for the 950 parts). The D main effect is found to be marginally significant for the 950 parts. The AH and CF interactions are found marginally significant for the kinkod950, and kinkod161 data respectively. This would suggest that, except for B with the 950 parts, none of the factors greatly affect kinking. The results for the re-analysis on the various fractions are generally consistent with this. No significant effects are found with most of the fractions. For the 950 parts, the B main effect is judged significant in two fractions and marginally significant in four others.

If, instead of using any formal statistical tests, the three largest effects for each analysis (Table 2 page 15) are examined, good consistency is seen across the different fractions. In Table 2 large capital letters indicate the factor is ranked in the top three with the full data, and small capital letters indicate that it is not. Generally, the effects chosen agree with those of the full analysis. The agreement is near perfect for the dish data. The bottom two sections of Table 2 show the percentage of times that the top three ranking effects in the full analysis appear in the top three rankings for the half fractions and quarter fractions respectively.

6 Conclusions

The main reason for performing this re-analysis was to determine whether an experiment using fewer runs would have yielded essentially the same recommended factor settings as the original experiment. All of the fractions considered in this study would suggest using the following settings:

1. H– level 1 (due to effect on dishing)
2. B– level 1 (due to effect on dishing)
3. C– level 1 (due to effect on dishing)

A few of the fractions would have had weak conflicting recommendations on the setting of factor B, with the dishing data strongly suggesting a low setting, and the kink 950 parts indicating a high setting. The recommendations made from the original experiment were:

1. H– level 1
2. B– level 2 (due to effect on pinion runout, and even though conflicts with the dish data)

3. C– level 1

4. A– level 1 (due to effect on pinion runout)

5. D– medium level (due to conflict between pinion runout and kinkod)

This study does not re-analyse the pinion runout data, or the 8.5 inch gear data, so we do not expect to duplicate conclusions based on these data sets. The original case study indicated the setting of A at level 1 was entirely due to the pinion runout data, as was the decision to set B at level 2 despite conflict with the dish data results. It can be assumed that the settings of D were based on conflicting recommendations from the pinion runout and the kink o.d. analyses for the 8.5 inch parts. With these points in mind, this study suggests that an experiment based on a quarter fraction of the original would have *yielded exactly the same recommendations* for the dish data (that is, setting H, B, C at their level 1). The much smaller effect of B on the kink950 data sets would probably have not been picked up.

These results suggest that a quarter fraction would have picked up the large effects, and only missed the marginal ones. Thus a more cost effective approach would be to set up a large design, but only implement a fraction of it on the first pass. If a few very large effects emerge, then setting them at optimum levels could completely solve the quality problems. Further experimentation would then be avoided. If little appears after the first pass, the rest of the runs can be performed to complete the design. This would give a more complete picture, and hopefully suggest optimum settings.

Factor Setting List:

A	Carbon Potential	Level 1 : 1.15%
		Level 2 : 1.40%
B	Operating Mode	Level 1 : Normal
		Level 2 : Continuous
C	Last Zone Temp.	Level 1 : 1500F
		Level 2 : 1650F
D	Quench Temperature	Level 1 : 300F
		Level 2 : 360F
E	Quench Agitation	Level 1 : 125rpm -0del
		Level 2 : 300rpm -5del
F	Tooth Size Deviat	Level 1 : Undersize
		Level 2 : Oversize
G	Tray Location	Level 1 : Left
		Level 2 : Right
H	Part Location	Level 1 : New
		Level 2 : Standard

Table 1

Significant Effects For Selected Fractions

Fraction	Kink i.d.		Kink o.d.		Dish	
	950	161	950	161	950	161
Full Data	B_2, d_1	—	B_2, a_1h_1, d_1	c_1f	H_1, B_1	H_1, B_1, C_1
I=+E	—	—	d_1	C_1F, B_2G	H_1, B_1	H_1, B_1, C_1
I=–E	—	—	b_2	—	H_1, B_1	H_1, B_1, C_1
I=+ABFGH	B_2	—	—	—	H_1, B_1	H_1, B_1, C_1
I=–ABFGH	—	—	—	—	H_1, B_1	H_1, B_1, C_1
I=+ADGH	b_2	—	B_2	—	H_1, B_1	H_1, B_1, C_1
I=–ADGH	—	—	—	—	H_1, B_1	H_1, B_1, C_1
I=+ABFG	—	—	—	—	H_1, B_1	H_1, B_1, C_1
I=–ABFG	—	—	b_2	—	H_1, B_1	H_1, B_1, C_1
I=+ADGH=+ABFG	—	—	—	—	H_1, B_1	H_1, B_1, C_1
I=–ADGH=+ABFG	—	—	—	—	H_1	H_1, B_1, C_1
I=+ADGH=–ABFG	—	—	—	—	H_1, B_1	H_1, B_1
I=–ADGH=–ABFG	—	—	b_2, ac	C_1H_1	H_1, B_1	H_1, B_1, C_1

Capital letters: Significant effects

Small letters: Marginally significant effects

Subscript: Recommended factor setting

Table 2

The 3 Top Ranked Effects For Selected Fractions

Fraction	Kink i.d.		Kink o.d.		Dish	
	950	161	950	161	950	161
Full Data	B, D, F	CE, B, CF	B, AH, D	CF, DF, BG	H, B, A	H, B, C
I=E	B, D, AB	CF, GH, BG	D, DG, CG	CF, BG, AB	H, B, C	H, B, C
I=-E	AH, B, F	A, F, GH	B, AH, DG	DF, A, C	H, B, CF	H, B, C
I=ABFGH	B, AH, H	BH, GH, F	AH, B, H	DF, BH, EF	H, B, A	H, B, C
I=-ABFGH	G, DH, D	C,BF, CE	D, EF, BH	CF, C, BD	H, B, A	H, B, C
I=ADGH	B, BC, G	CE, BC, CH	B, CG, F	CE, EF, FH	H, B, A	H, B, C
I=-ADGH	CD, F, D	BC, AG, FH	D, CD, BE	FH, CH, DF	H, B, CF	H, B, C
I=ABFG	D, B, F	B, BD, F	F, D, AC	BD, DF, DG	H, B, A	H, B, C
I=-ABFG	B, GH, A	G, CE, EG	B, A ,CF	G, B, CF	H, B, CF	H, B, C
I=ADGH=ABFG	B, F, AC	CH, B, DE	F, AC, B	CH, BE, CE	H, B, C	H, B, C
I=-ADGH=ABFG	AH, E, CE	EF, BE, G	B, CF, AH	B, EF, BE	H, AG, B	H, B, C
I=ADGH=-ABFG	D, CD, AH	B, BD, AG	D, AB, CH	FH, BD, BH	H, B, AG	H, B, AF
I=-ADGH=-ABFG	F, BE, B	CH, CG, G	B, AC, A	CH, EF, G	H, B, CF	H, B, C
% of 1/2 Fractions	B–75%	CE–38%	B–50%	CF–38%	H–100%	H–100%
Containing	D–50%	B–13%	AH–25%	DF–50%	B–100%	B–100%
Fulldata Effects	F–38%	CF–13%	D–50%	BG–13%	A–50%	C–100%
% of 1/4 Fractions	B–50%	CE–0%	B–75%	CF–0%	H–100%	H–100%
Containing	D–25%	B–50%	AH–25%	DF–0%	B–100%	B–100%
Fulldata Effects	F–50%	CF–0%	D–25%	BG–0%	A–0%	C–75%

Large letters: Effects in top three for fulldata which recur in selected fractions

Small letters: Effects not in top three for fulldata

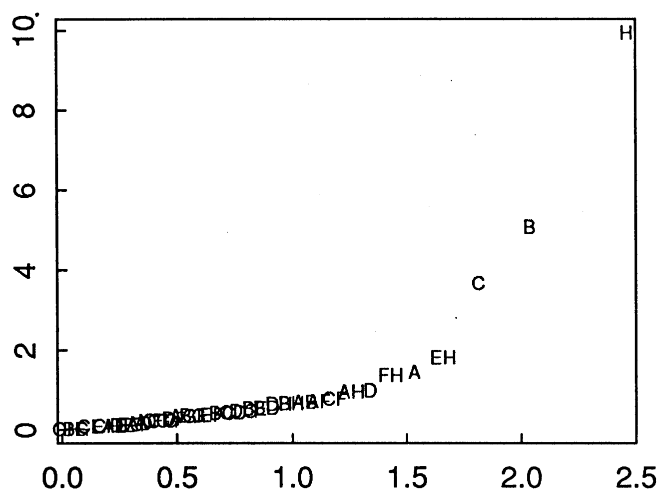
7 References

Shoemaker, A.S., Tsui, K.-L., and Wu, C.F.J. (1989), "Economical Experimentation Methods for Robust Parameter Design" *IIQP Research Report*, RR-89-04. To appear in *Technometrics.*

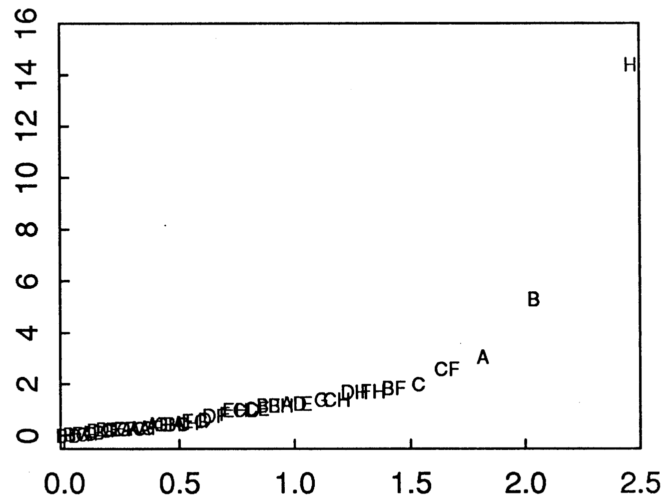
Taguchi, G. (1987), *System of Experimental Design*, Unipub/Kraus International Publications, White Plains, New York.

Complete Data
Half Normal Plots

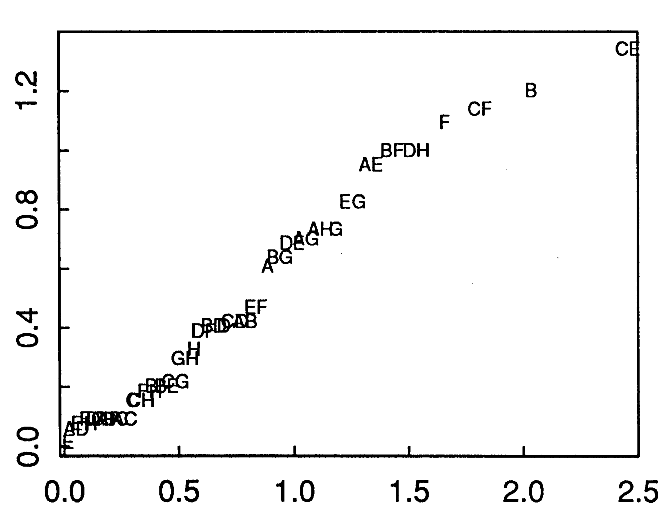
Dish161



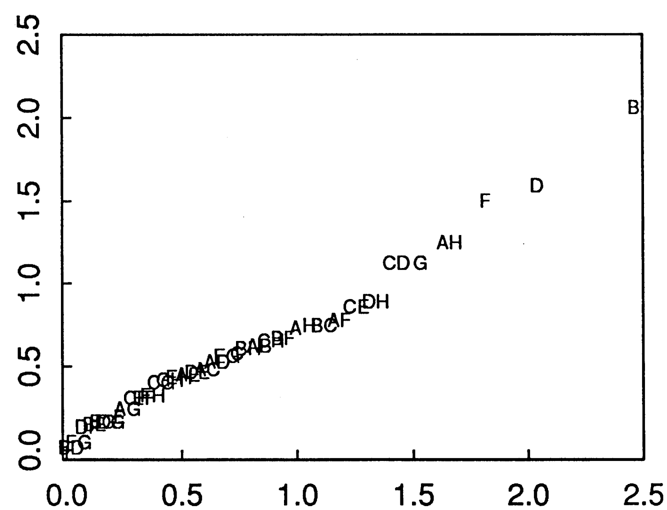
Dish950



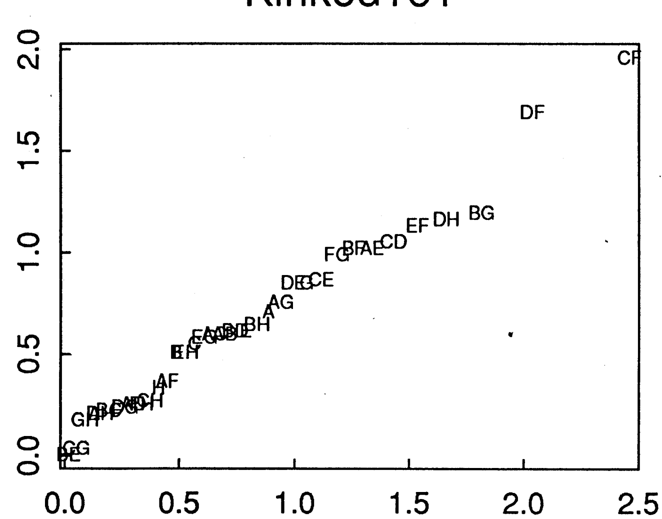
Kinkid161



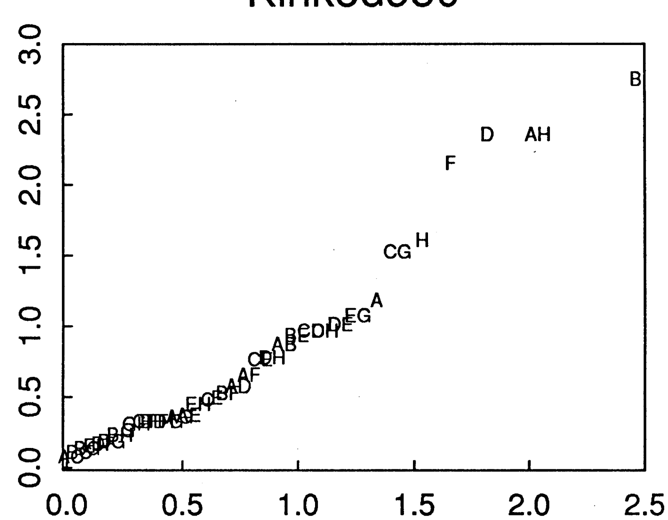
Kinkid950



Kinkod161



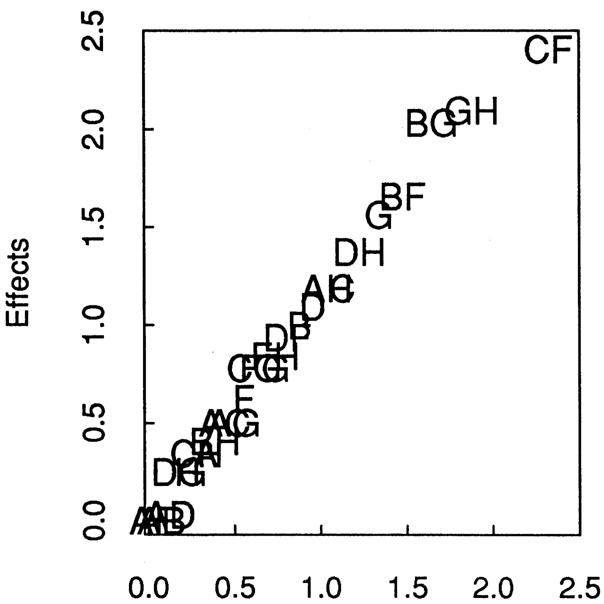
Kinkod950



E Splits

Half Normal Plots for Kinkid Data

Kinkid161: I=E



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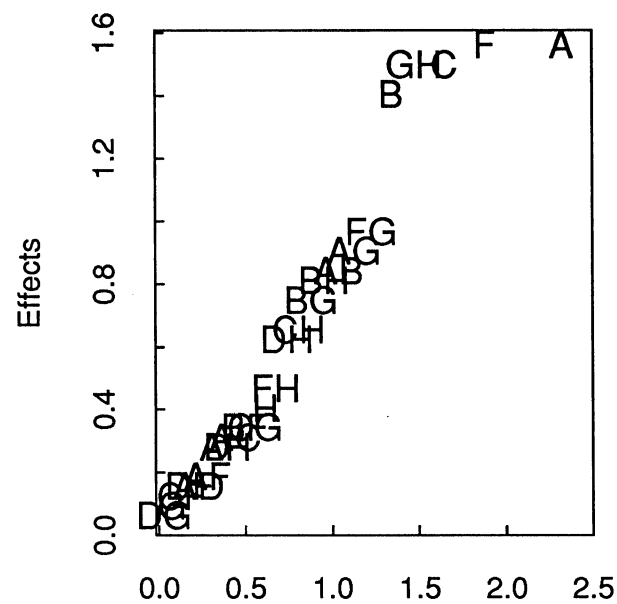

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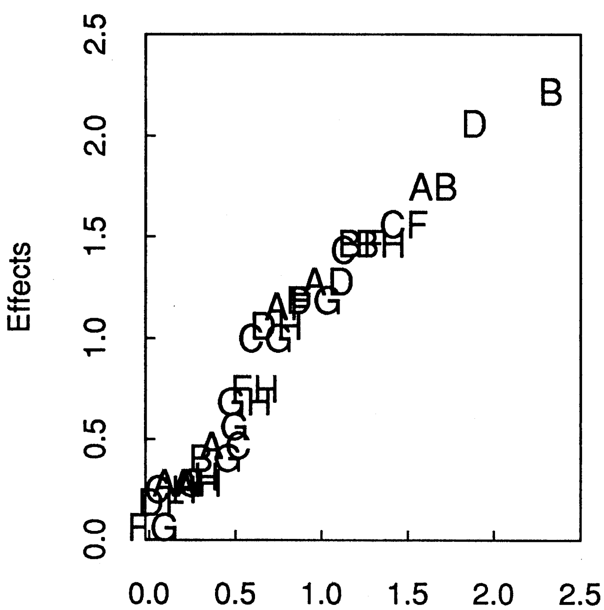
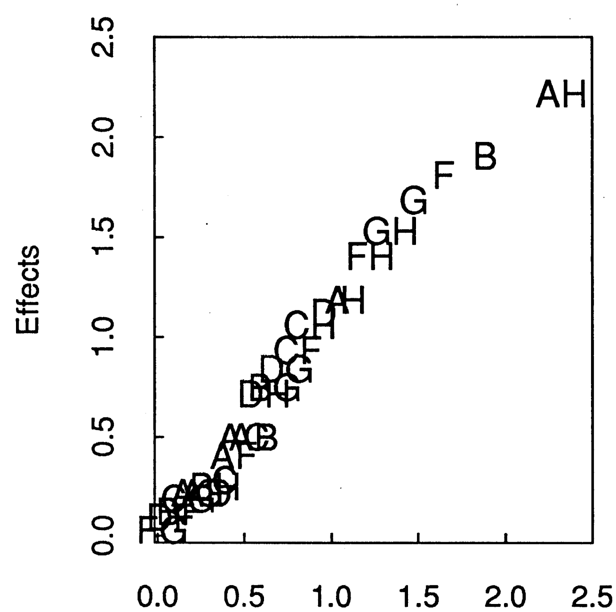


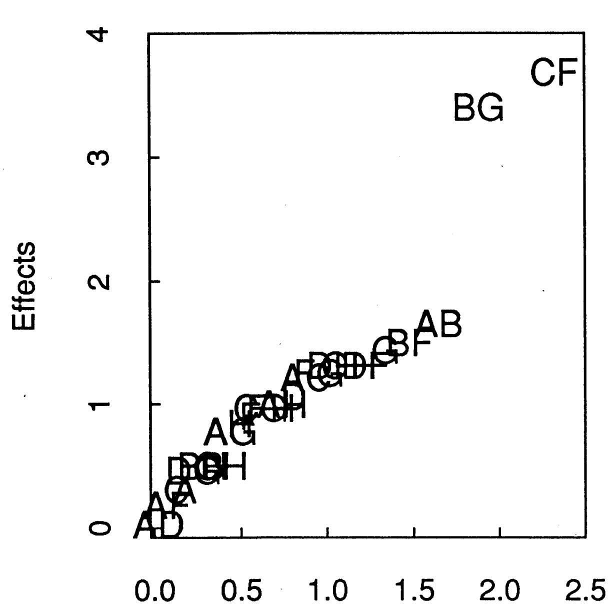
Kinkid950: I=- E



E Splits

Half Normal Plots for Kinkod Data

Kinkod161: I=E



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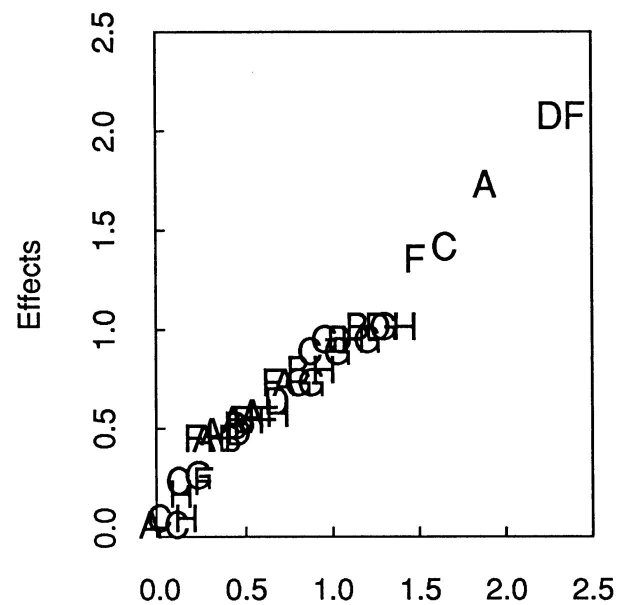
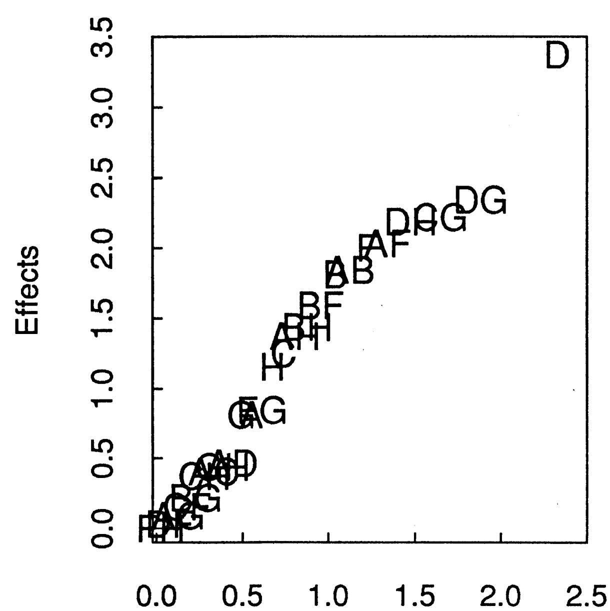


Kinkod950: I=E



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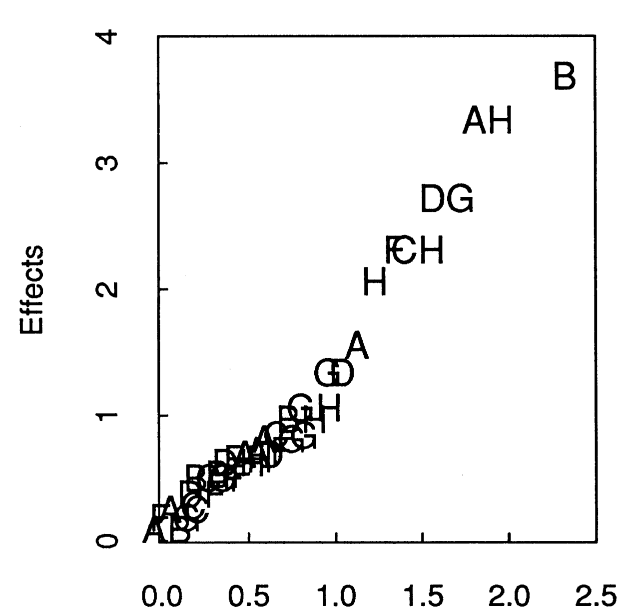
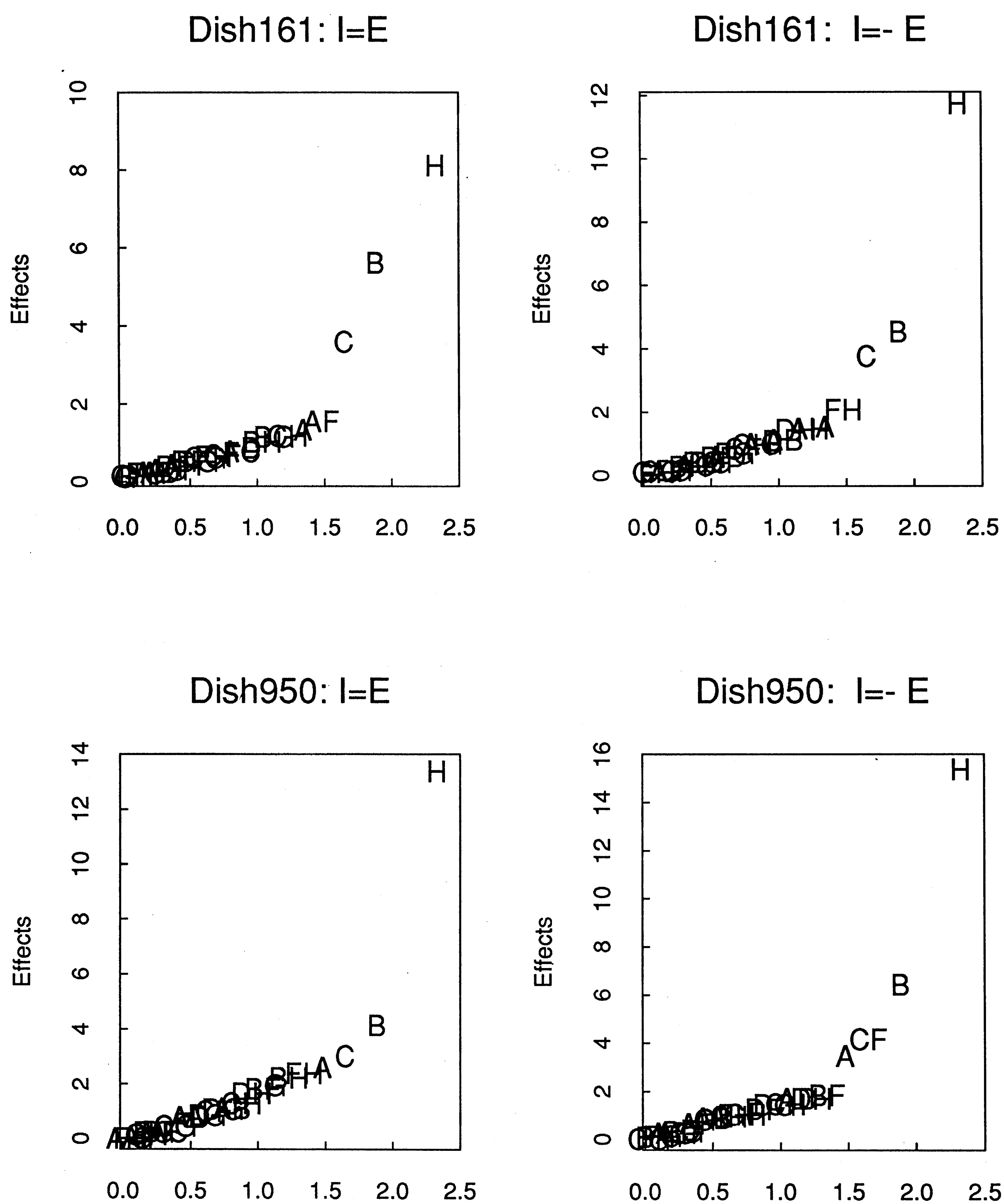


E Splits

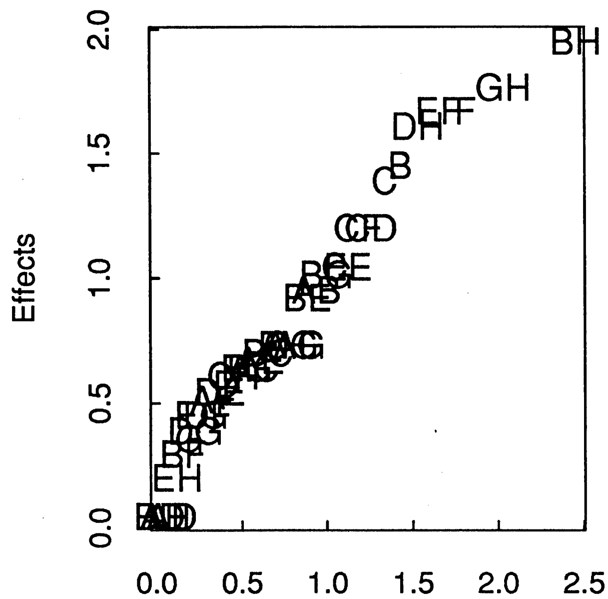
Half Normal Plots for Dish Data



ABFGH Splits

Half Normal Plots for Kinkid Data

Kinkid161: I=ABFGH



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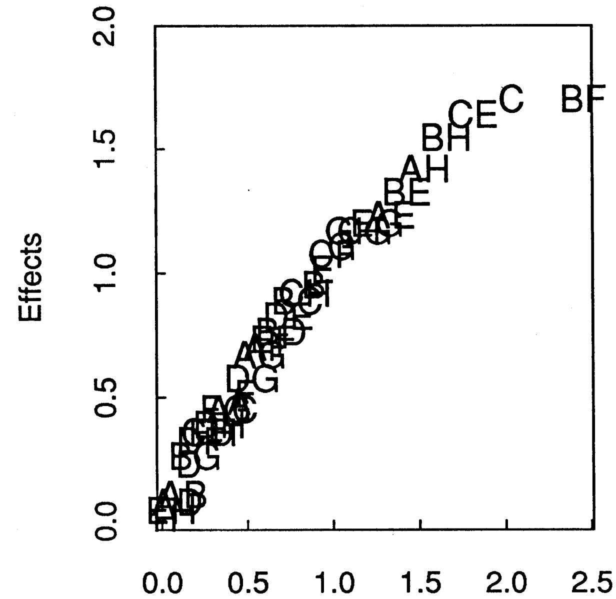
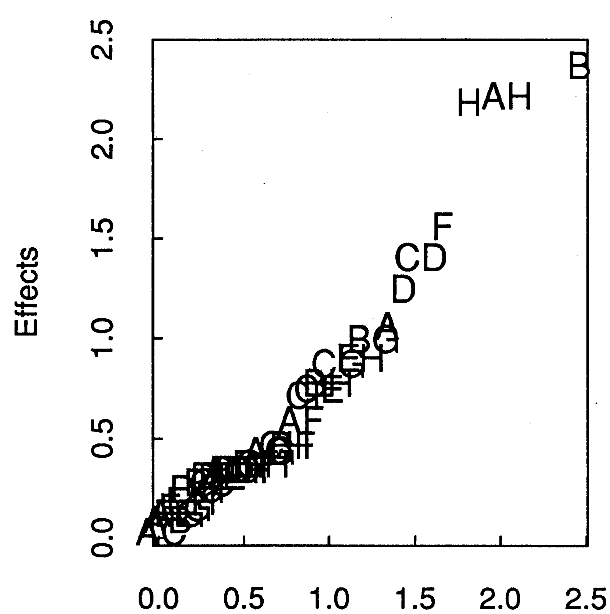
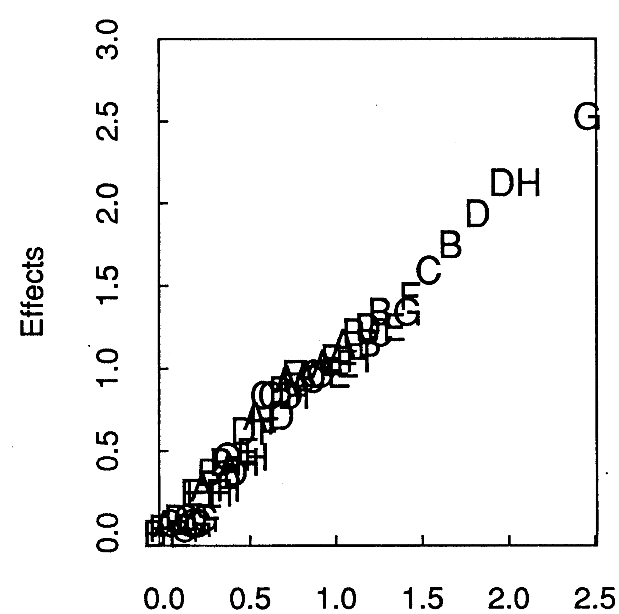


Kinkid950: I=ABFGH



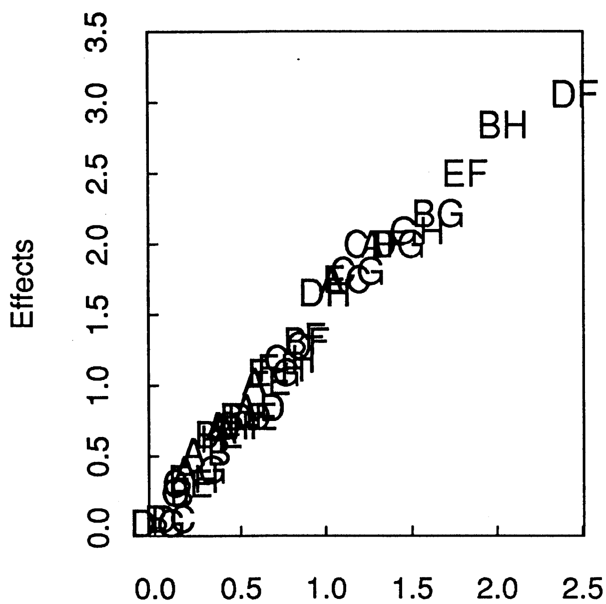
Kinkid950: I=-ABFGH



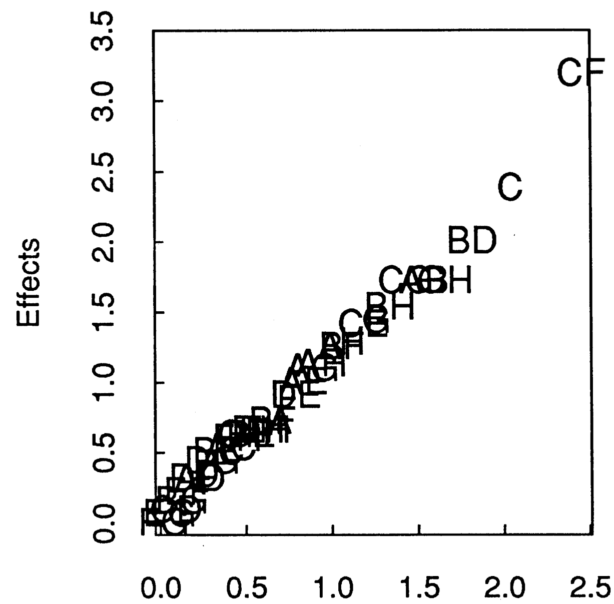
ABFGH Splits

Half Normal Plots for Kinkod Data

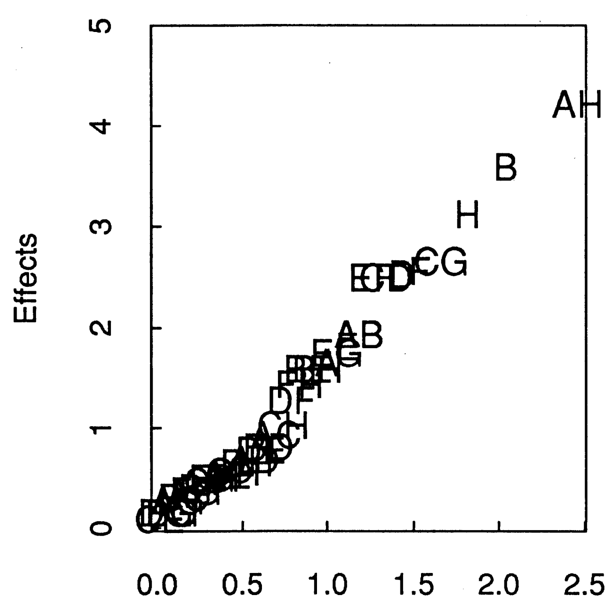
Kinkod161: I=ABFGH



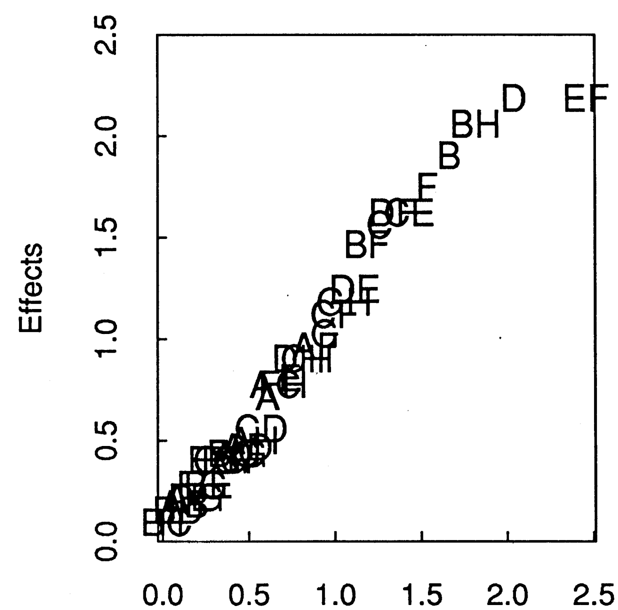
Kinkod161: I=-ABFGH



Kinkod950: I=ABFGH



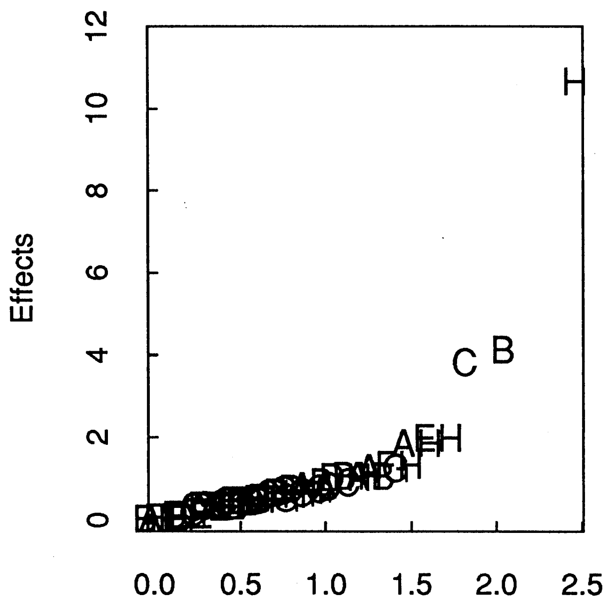
Kinkod950: I=-ABFGH



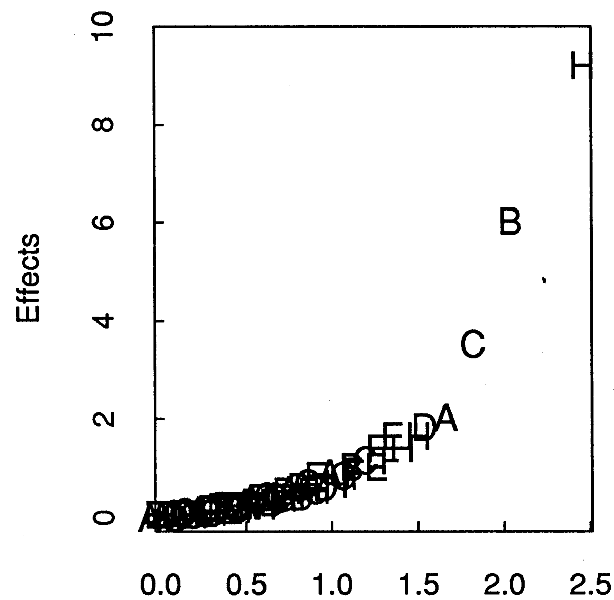
ABFGH Splits

Half Normal Plots for Dish Data

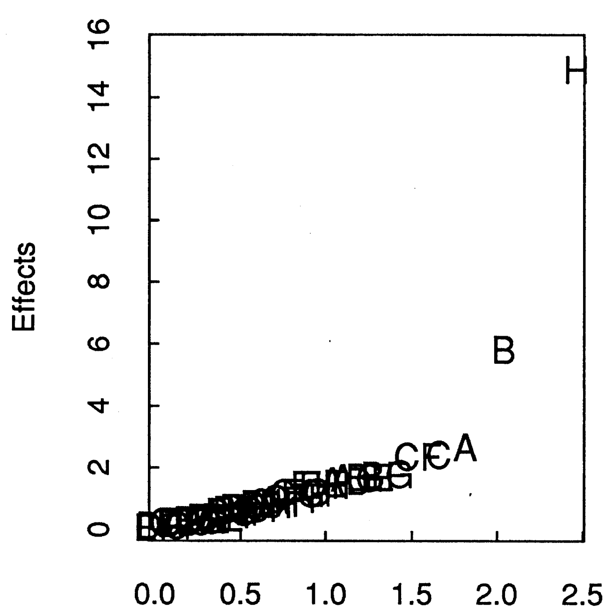
Dish161: I=ABFGH



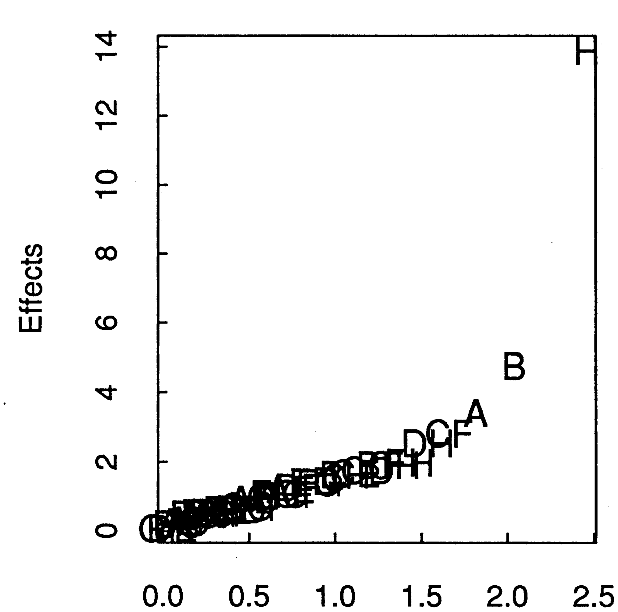
Dish161: I=-ABFGH



Dish950: I=ABFGH



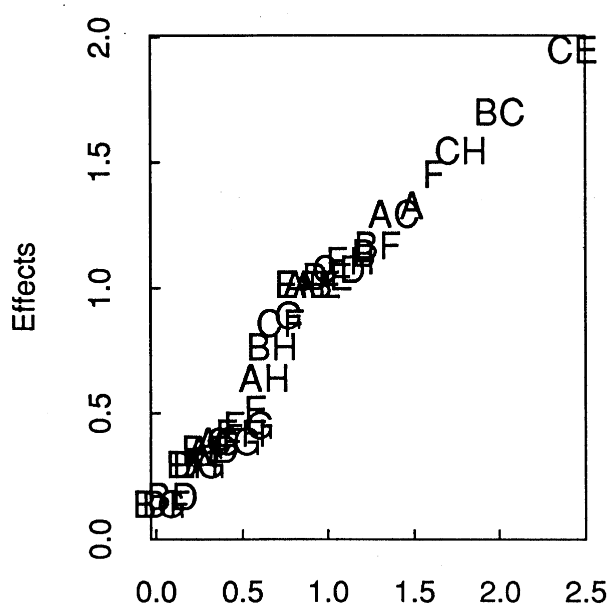
Dish950: I=-ABFGH



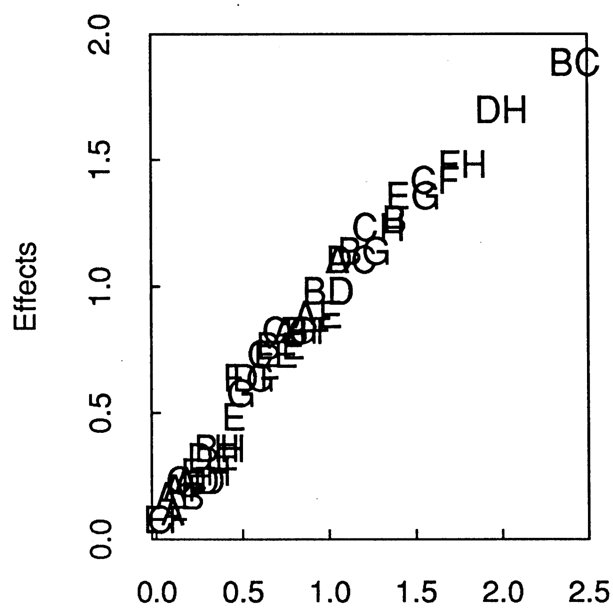
ADGH Splits

Half Normal Plots for Kinkid Data

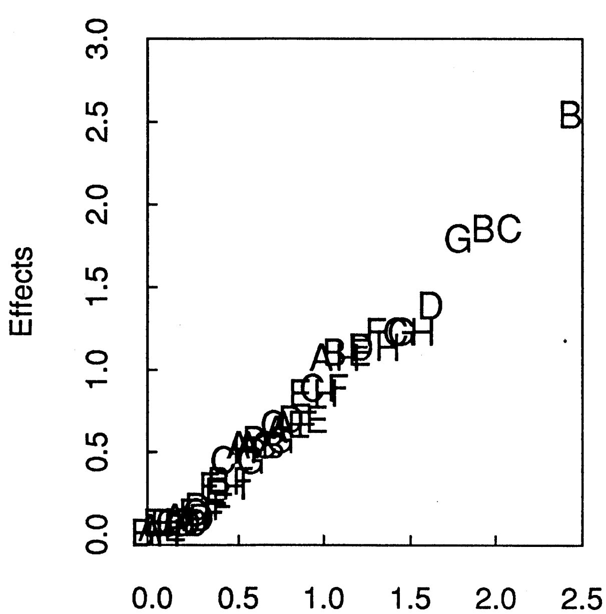
Kinkid161: I=ADGH



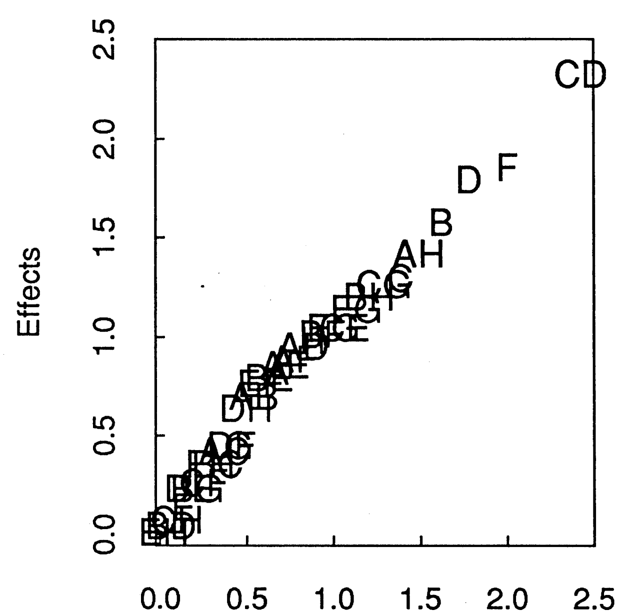
Kinkid161: I=- ADGH



Kinkid950: I=ADGH



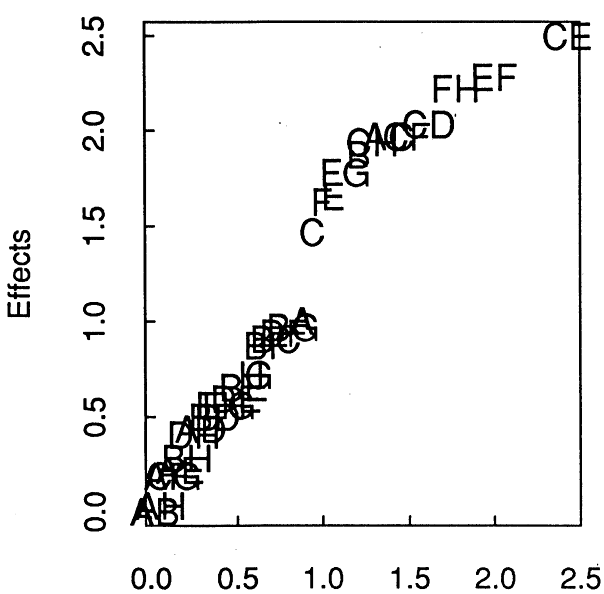
Kinkid950: I=- ADGH



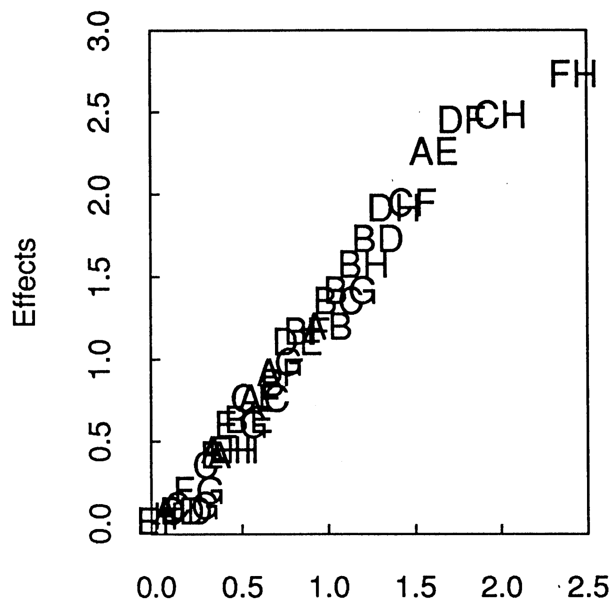
ADGH Splits

Half Normal Plots for Kinkod Data

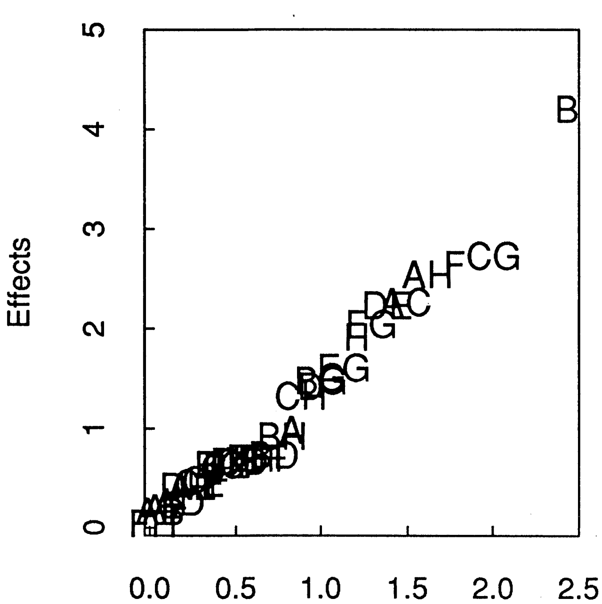
Kinkod161: I=ADGH



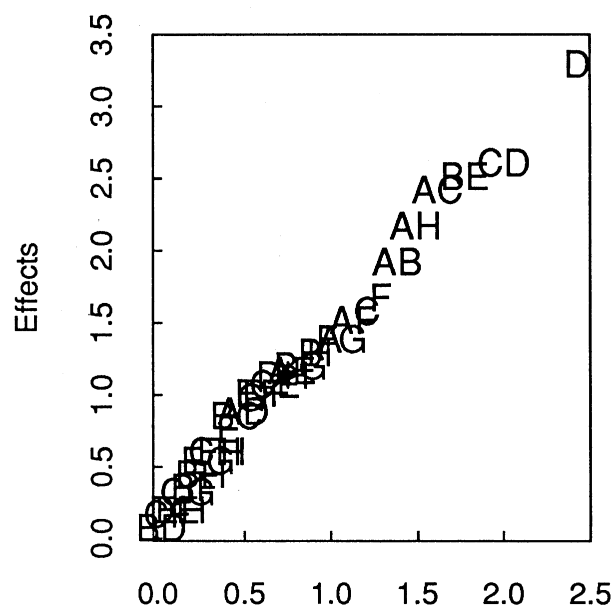
Kinkod161: I=- ADGH



Kinkod950: I=ADGH

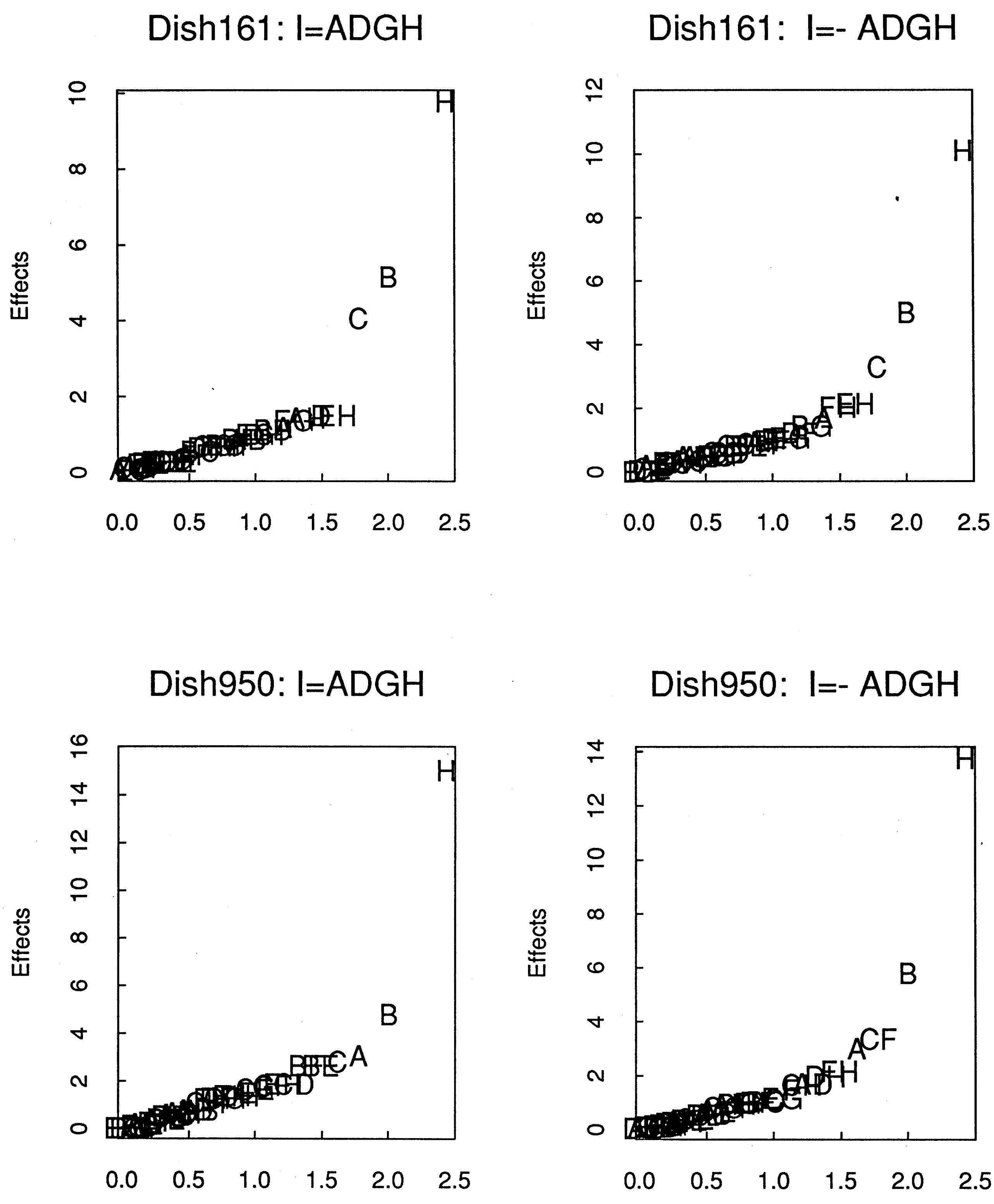


Kinkod950: I=- ADGH



ADGH Splits

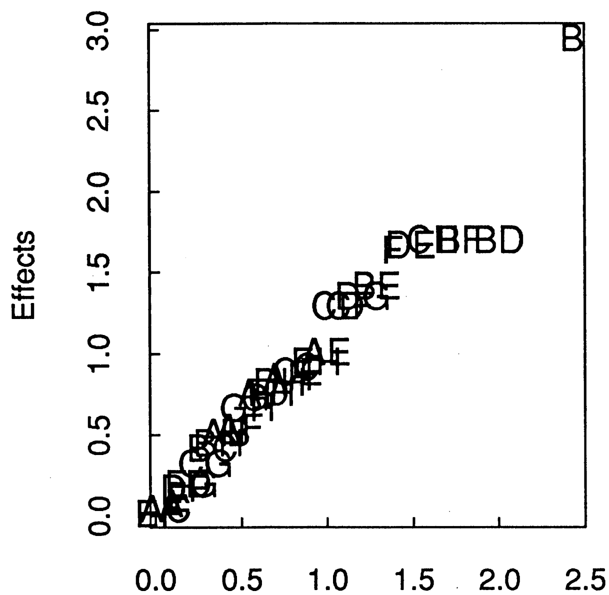
Half Normal Plots for Dish Data



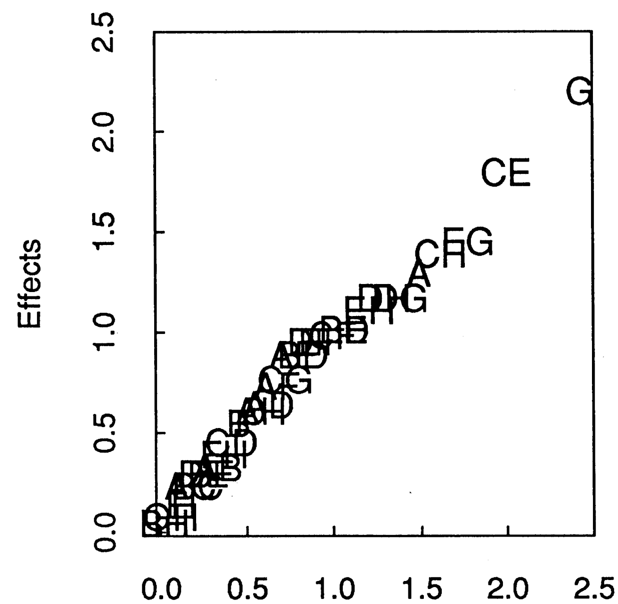
ABFG Splits

Half Normal Plots for Kinkid Data

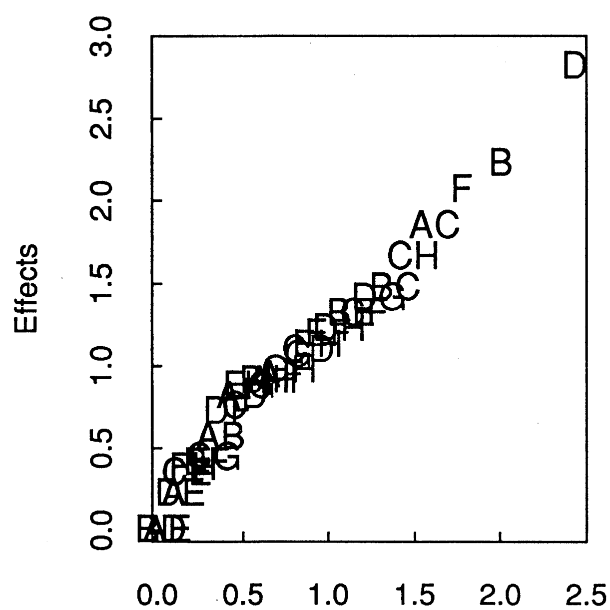
Kinkid161: I=ABFG



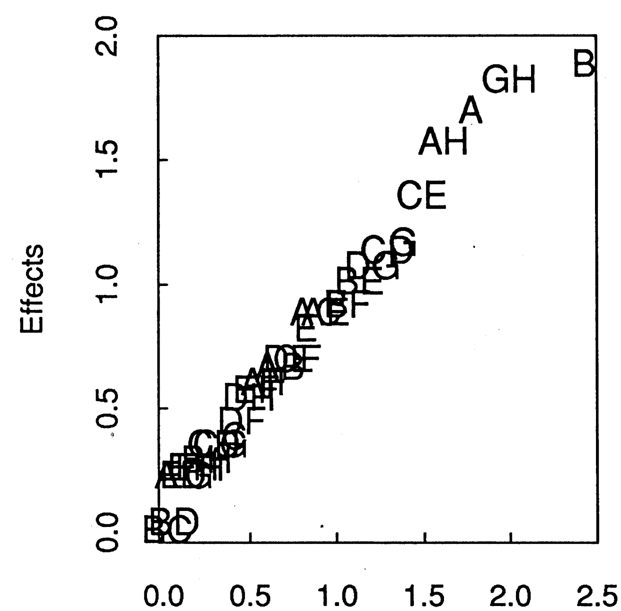
Kinkid161: I=- ABFG



Kinkid950: I=ABFG



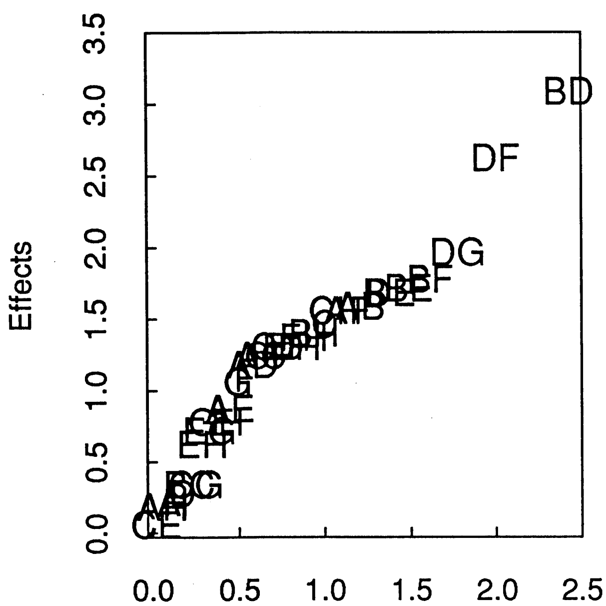
Kinkid950: I=- ABFG



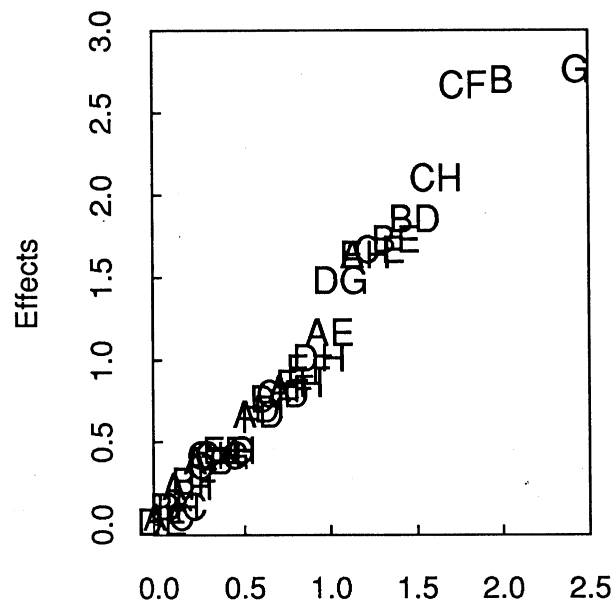
ABFG Splits

Half Normal Plots for Kinkod Data

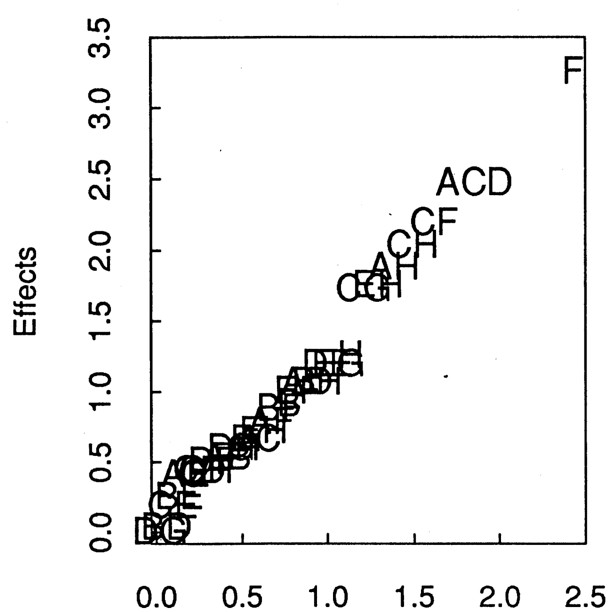
Kinkod161: I=ABFG



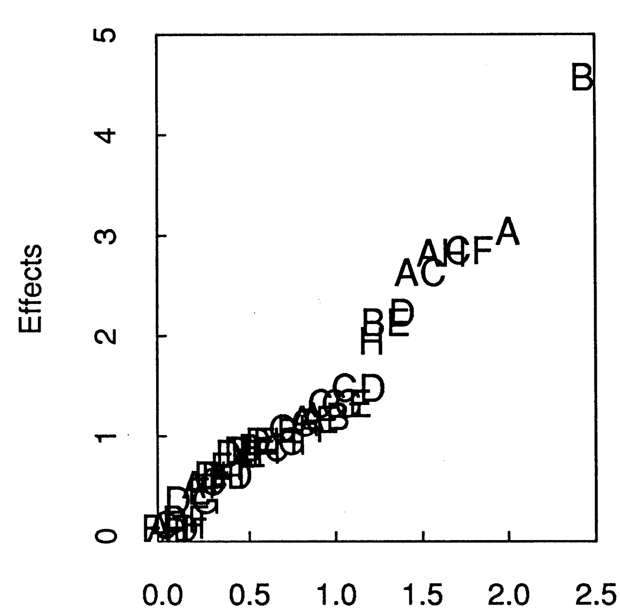
Kinkod161: I=- ABFG



Kinkod950: I=ABFG

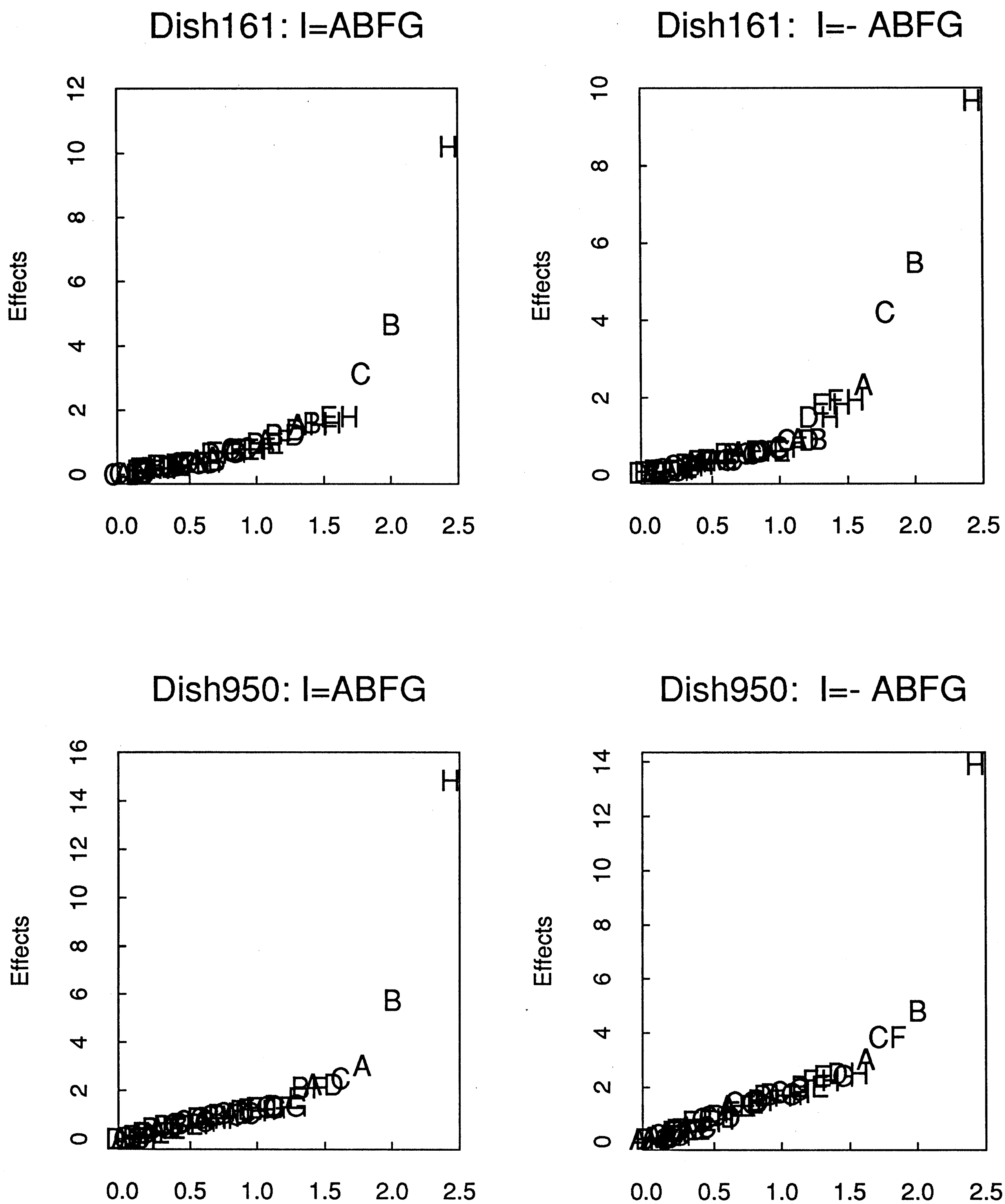


Kinkod950: I=- ABFG



ABFG Splits

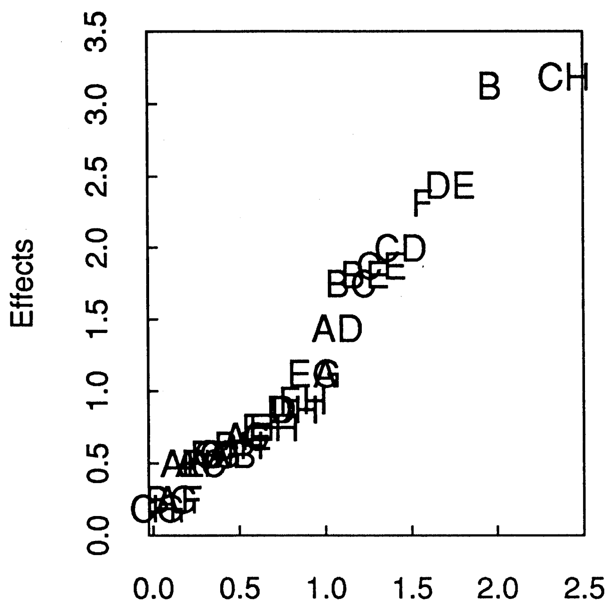
Half Normal Plots for Dish Data



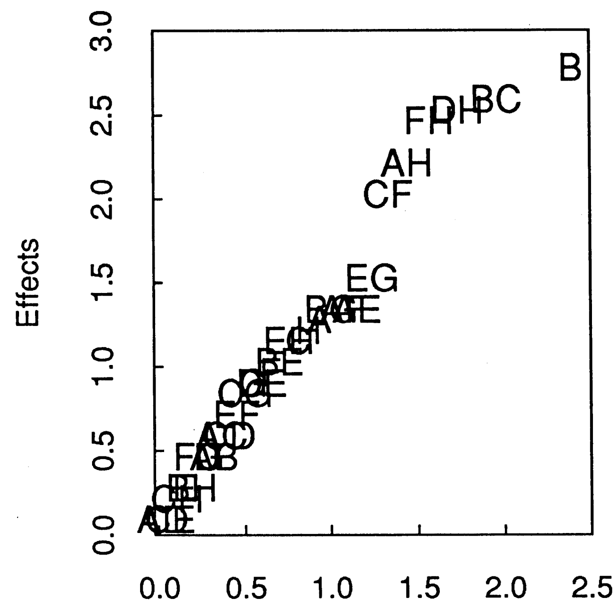
Quarter Splits

Half Normal Plots for Kinkid161 Data

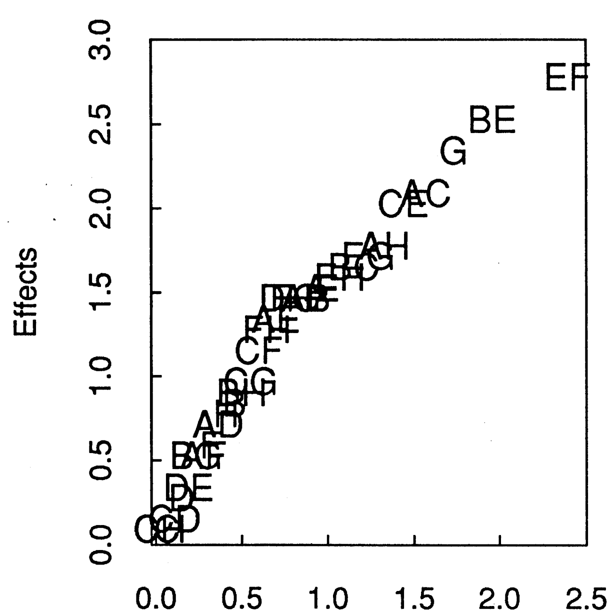
I= ABFG=ADGH



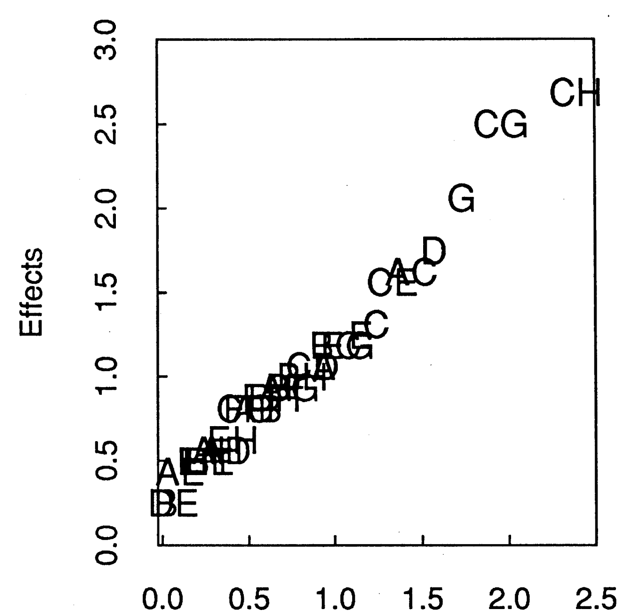
I= ABFG=-ADGH



I=- ABFG=ADGH



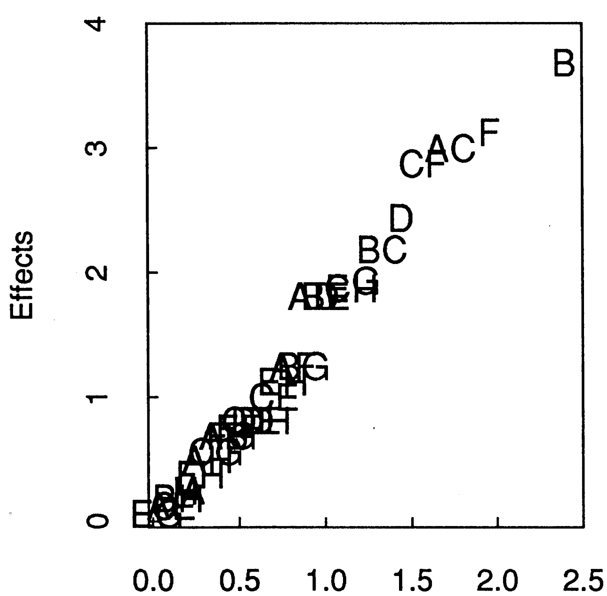
I=- ABFG=-ADGH



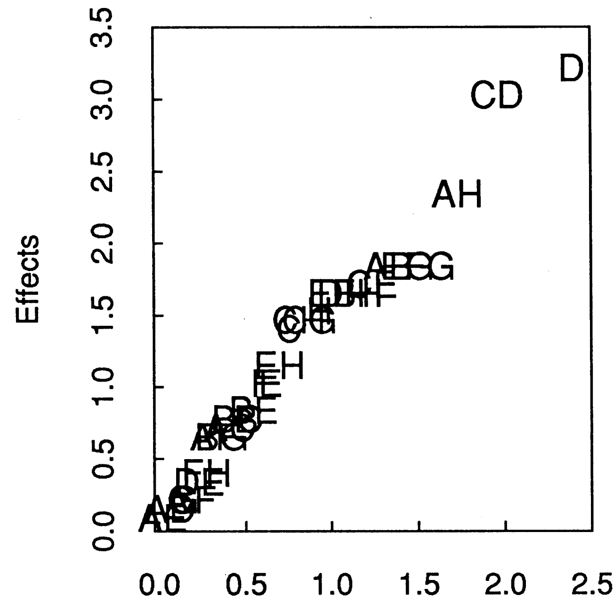
Quarter Splits

Half Normal Plots for Kinkid950 Data

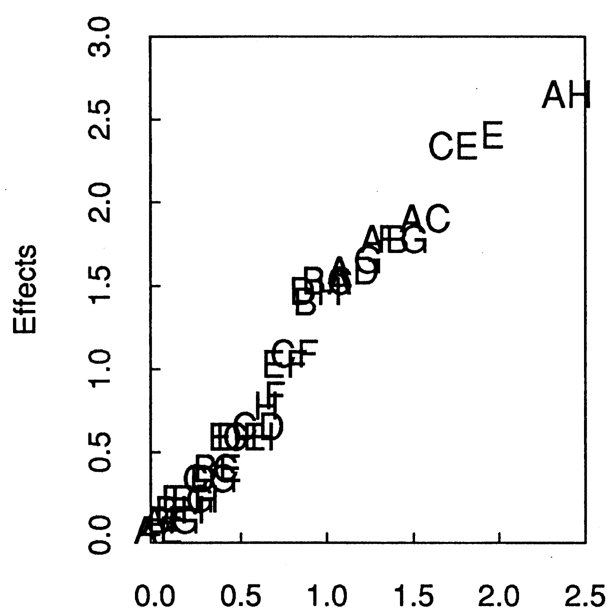
I= ABFG=ADGH



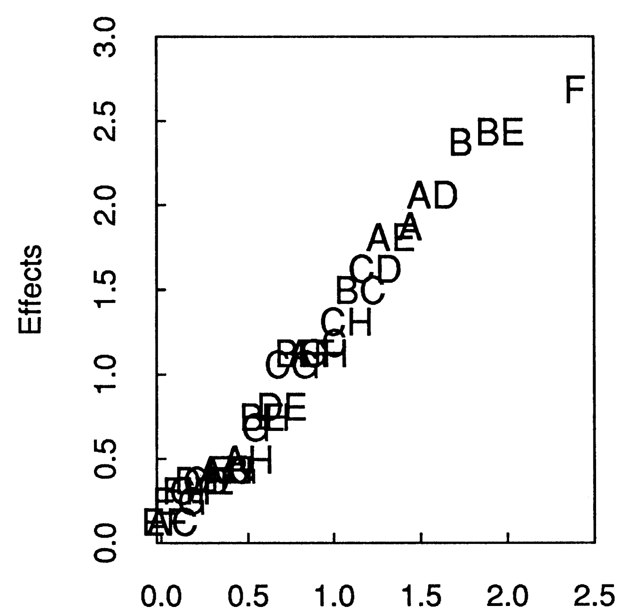
I= ABFG=-ADGH



I=- ABFG=ADGH

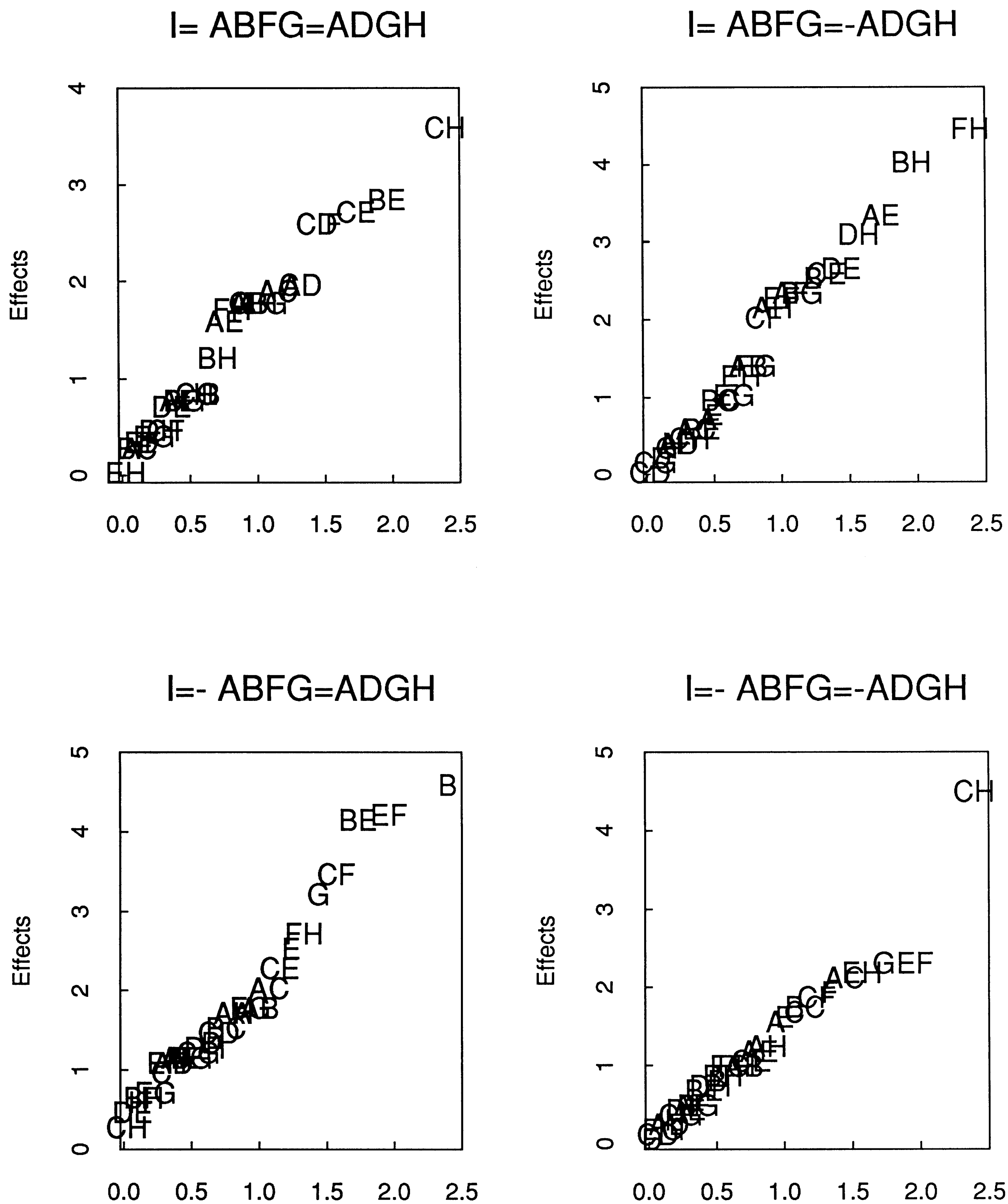


I=- ABFG=-ADGH



Quarter Splits

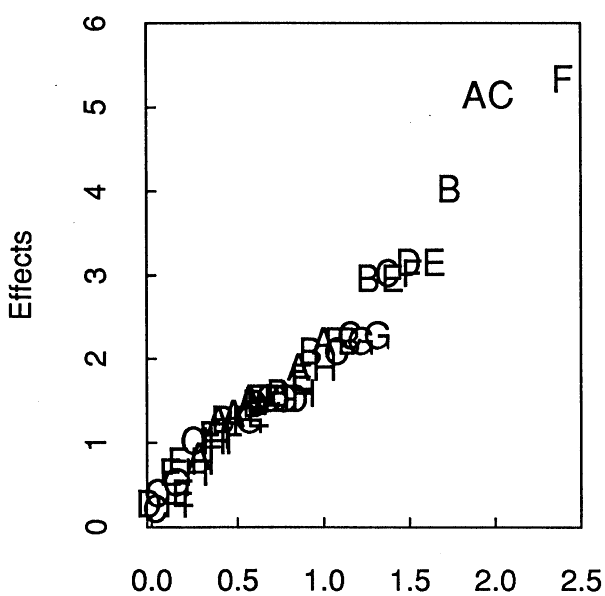
Half Normal Plots for Kinkod161 Data



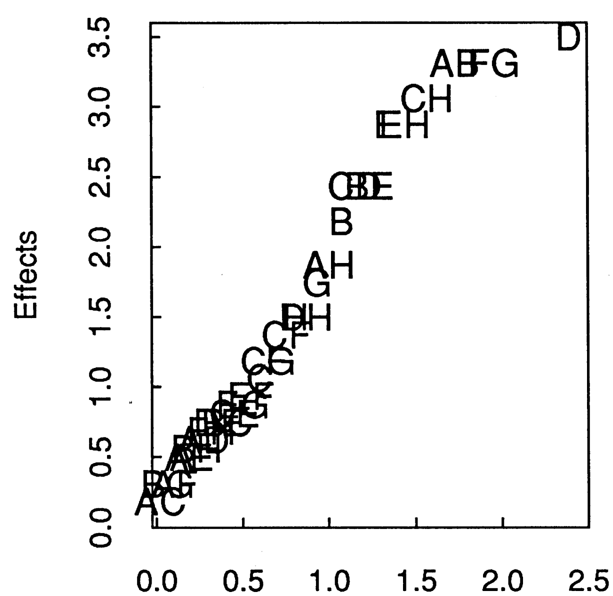
Quarter Splits

Half Normal Plots for Kinkod950 Data

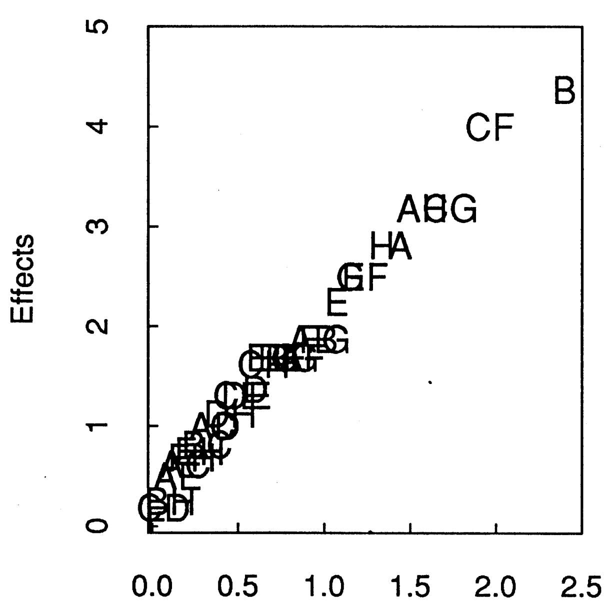
I= ABFG=ADGH



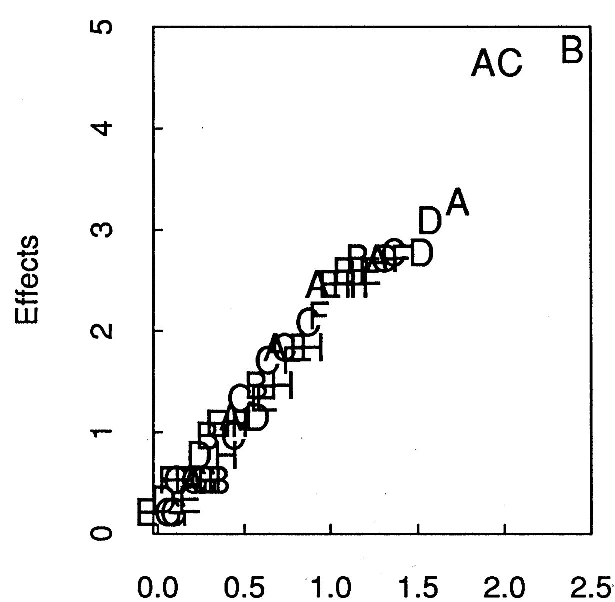
I= ABFG=-ADGH



I=- ABFG=ADGH

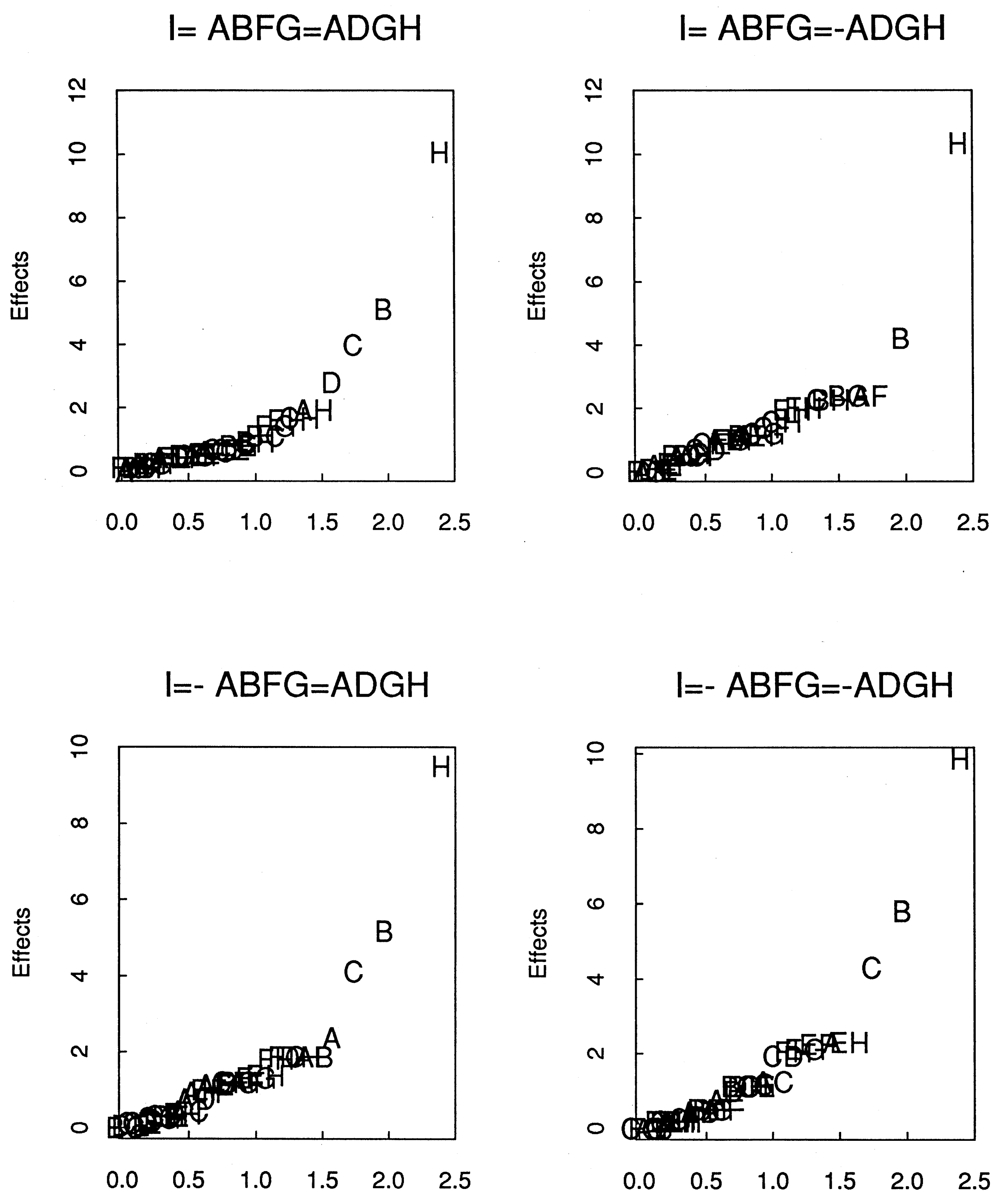


I=- ABFG=-ADGH



Quarter Splits

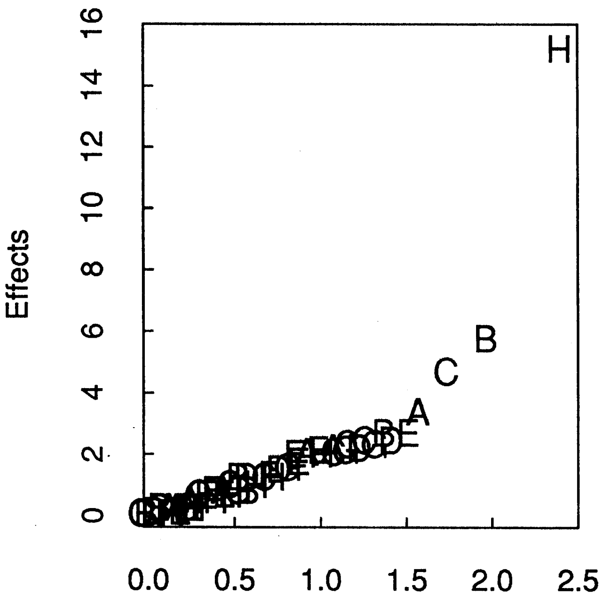
Half Normal Plots for Dish161 Data



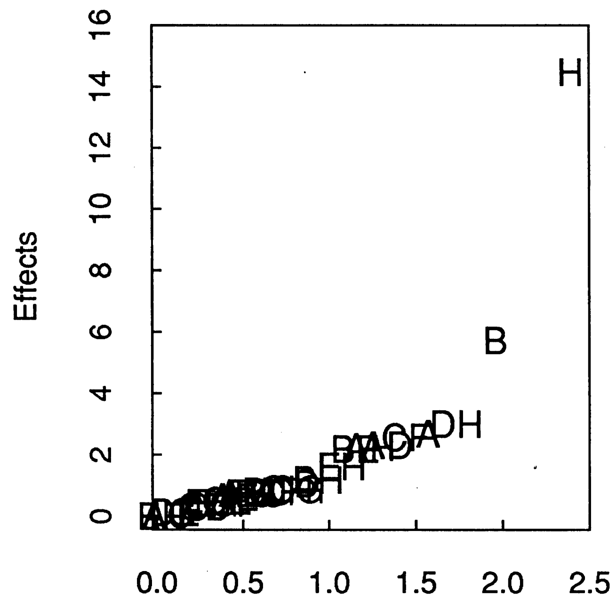
Quarter Splits

Half Normal Plots for Dish950 Data

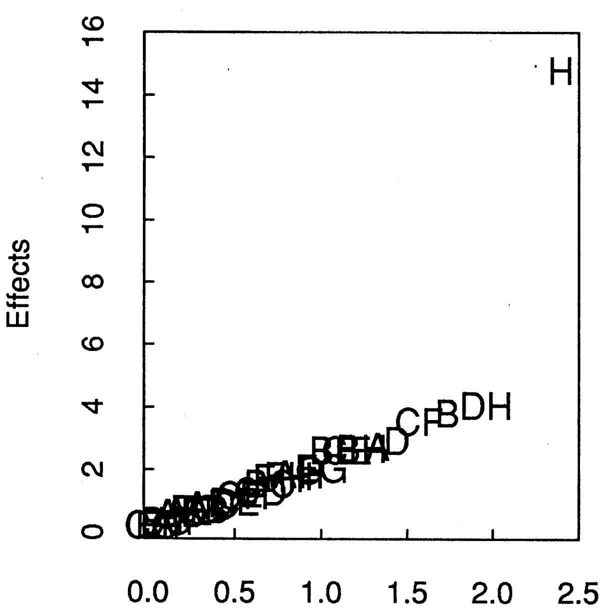
I= ABFG=ADGH



I= ABFG=-ADGH



I=- ABFG=ADGH



I=- ABFG=-ADGH