Genetic Etiology of Spelling Deficits in the Colorado and London Twin Studies of Reading Disability

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ABSTRACT: The basic multiple regression model for the analysis of selected twin data (DeFries and Fulker 1985, 1988) was fitted to spelling data from 100 pairs of MZ twins and 71 pairs of same-sex DZ twins tested in the Colorado Reading Project (DeFries, Olson, Pennington and Smith 1991), and to data from 12 pairs of MZ twins and 15 pairs of same-sex DZ twins tested in the London twin study of reading disability (Stevenson, Graham, Fredman and McLoughlin 1984, 1987). Estimates of h_g^2 obtained from analyses of these data suggest that about 60% of the deficit of probands is due to heritable influences in both samples. When a regression model was fitted separately to data from males and females in the combined Colorado and London samples, resulting estimates of h_g^2 were 0.66 $\pm$ 0.18 and 0.56 $\pm$ 0.19, respectively, a nonsignificant difference. Collaborative analyses of data from additional twin studies of reading disability would facilitate more rigorous tests of hypotheses of differential genetic etiology as a function of group membership.

KEYWORDS: Spelling, reading disability, genetics, etiology, twins.

Previous twin studies of reading disability (Zerbin-Rüdin 1967, Bakwin 1973, and Stevenson, Graham, Fredman and McLoughlin 1984 and 1987) employed a comparison of concordance rates in identical (monozygotic, MZ) and fraternal (dizygotic, DZ) twin pairs as a test for genetic etiology. A pair is concordant if both members of the pair manifest a condition, but discordant if only one member is affected. Thus, a genetic etiology is indicated if the MZ concordance rate for a condition exceeds that for DZ twin pairs.

Although the concept for concordance is conceptually very simple, its estimation is dependent upon the method of sample ascertainment. For example, if a sample of twins is ascertained by "single selection" in which only one member of a pair could be selected as a proband, then "pairwise" concordance is appropriate. However, if "truncate selection" is employed in which both affected members of a twin pair could be ascertained as probands, then "probandwise" concordance should be computed. To estimate probandwise concordance, members of concordant pairs are counted twice, once as a proband and once as a cotwin (see DeFries and Gillis, 1991). Because subjects in previous twin studies of reading dis-

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ability were likely ascertained employing truncate selection, probandwise concordance rates will be reported in this brief review.

Concordance Rates in Twin Studies of Reading Disability

Zerbin-Rüdin (1967) reviewed data from six case studies of twins with "congenital word-blindness" (5 MZ pairs and 1 DZ pair), a Danish twin study (Norrie 1954, Hermann and Norrie 1958) that included 9 MZ and 30 DZ pairs, and data from 3 MZ and 3 DZ twin pairs included in Hallgren's (1950) classic family study of dyslexia. In this combined sample of 17 pairs of identical twins and 34 pairs of fraternal twins, the probandwise concordance rates are 100% and 52%, respectively. Bakwin (1973) ascertained pairs of same-sex twins through mothers-of-twins clubs and obtained reading history information from parents via interviews, telephone calls, and mail questionnaires. In 31 pairs of identical twins and 31 pairs of fraternal twins in which at least one member of each pair met his criterion for reading disability, the probandwise concordance rates are 91% and 45%. Although these two early publications are based upon data from very different samples, it is interesting to note that their estimated probandwise concordance rates are highly similar.

More recently, Stevenson et al. (1984, 1987) reported results from the first twin study of reading disability in which twin pairs were ascertained from the general population and independently tested using standardized measures of intelligence and of reading and spelling performance. A sample of 285 pairs of 13-year-old twins was obtained by screening hospital records in five London boroughs or through primary schools in the London area. Twins were diagnosed for reading or spelling "backwardness" or "retardation," where backwardness was identified by the presence of reading or spelling performance below that expected based on chronological age, and retardation was defined by marked underachievement in reading or spelling relative to that predicted from IQ and chronological age. Probandwise concordance rates employing these various diagnostic criteria ranged from 33% to 59% for MZ twins and from 29% to 54% for fraternal twins. Stevenson et al. (1987) speculated that the lower concordance rates for reading disability obtained in the London study may have been due to differences in age of subjects, method of sample ascertainment, definition of disability, or zygosity determination.

A more extensive twin study of reading disability was initiated in 1982 as part of the ongoing Colorado Reading Project (Decker and Vandenberg 1985, DeFries 1985). A psychometric test battery that includes the WISC-R (1974) or the Wechsler Adult Intelligence Scale-Revised (WAIS-R; Wechsler 1981) and the Peabody Individual Achievement Test (PIAT; Dunn and Markwardt 1970) is currently being administered to MZ and

DZ twin pairs in which at least one member of each pair is reading disabled and to a comparison group of twins with no history of reading problems. In a recent report (DeFries and Gillis 1991) data from the PIAT Reading Recognition, Reading Comprehension, and Spelling subtests were used to compute a discriminant function score for each member of the pair. Twin pairs were included in the proband sample if at least one member of the pair with a positive school history for reading problems was classified as affected by the discriminant score and met additional criteria for proband diagnosis. In a sample of 96 pairs of MZ twins, 72 pairs of same-sex DZ twins, and 24 pairs of opposite-sex DZ twins in which at least one member of each pair met the criteria for reading disability, the probandwise MZ and DZ concordance rates were 71% and 49%, respectively.

Multiple Regression Analysis of Twin Data

Although a comparison of concordance rates is appropriate for categorical variables (e.g., presence or absence of a disease state), reading disability is diagnosed on the basis of a continuous measure such as reading or spelling performance with arbitrary cut-off points (Stevenson et al. 1987). For such variables, a comparison of MZ and DZ cotwin means is more appropriate than a comparison of concordance rates as a test for genetic etiology (DeFries and Fulker 1985). When probands have been ascertained because of highly deviant scores on a continuous measure, the scores of both the MZ and DZ cotwins should regress toward the mean of the unselected population. However, to the extent that the condition has a genetic etiology, scores of DZ cotwins should regress more toward the mean of the unselected population. Thus, if the means for the MZ and DZ probands were equal, a *t*-test of the difference between the means of the MZ and DZ cotwins would suffice as a test for genetic etiology. However, fitting a multiple regression model to selected twin data, in which the cotwin's score is predicted from the proband's score and the coefficient of relationship, provides a more general and statistically more powerful test (DeFries and Fulker 1985, 1988). Moreover, a simple transformation of twin data prior to multiple regression analysis facilitates direct estimates of h_g^2, an index of the extent to which the deficit of probands is due to heritable influences. For example, DeFries and Gillis (1991) obtained an estimate of $h_g^2 = 0.50 \pm 0.11$ for a composite measure of reading performance when the multiple regression model was fitted to data from probands and cotwins tested in the Colorado Reading Project. This result suggests that about one-half of the reading performance deficit of probands, on average, is due to heritable factors.

The multiple regression analysis of selected twin data is a highly flexible

methodology. For example, the basic model can be easily extended to include other main effects such as age, IQ, or socioeconomic status. Interactions between main effects can also be added to the regression model (Cohen and Cohen 1975) to assess differential genetic etiology as a function of group membership (e.g., sample or gender).

In order to increase the number of reading-disabled MZ and DZ twin pairs available for multiple regression analysis, we have recently initiated a collaborative analysis of data collected in the Colorado and London twin studies of reading disability. Although multiple regression analysis was applied previously to a composite measure of reading performance in the Colorado study (e.g., DeFries, Fulker and LaBuda 1987, DeFries and Gillis 1991), differences between the Colorado and London test batteries made it difficult to create a comparable composite reading measure for the two studies. Stevenson et al. (1984) have previously suggested that genetic influences on literacy problems are more appropriately studied through their impact on spelling than on measures of word recognition or reading comprehension. There are several reasons for postulating that spelling may be less susceptible than reading to environmental influences. First, there is evidence that spelling performance of reading-disabled children improves less over time than does reading (Rutter and Yule 1975, Critchley and Critchley 1978). Second, spelling is a more constrained task than reading. Because there are fewer contextual clues to spelling vis-a-vis word naming, there is a greater scope for remediating reading difficulties. Third, genetic etiology may differ more as a function of age for reading than for spelling deficits (Wadsworth, Gillis, DeFries and Fulker 1989). Thus, in this first report, we focus upon spelling deficits and present estimates of h_g^2 for the current Colorado sample, the London sample, and a pooled estimate obtained from our combined data sets.

Recent studies have indicated that reading-disabled females obtained somewhat higher average spelling scores than males (Vogel 1990, DeFries, Wadsworth and Gillis 1990), and there is some limited evidence for a differential genetic etiology of reading deficits in males and females (DeFries, Gillis and Wadsworth, in press). Allred (1990) has recently discussed gender differences in spelling achievement and suggested that additional information concerning the etiology of these differences is needed. We, therefore, also tested the hypothesis of differential genetic etiology of spelling deficits as a function of gender in the combined sample.

METHOD

Subjects. Twin pairs are identified in the Colorado Reading Project by administrators of school districts within a 150-mile radius of Boulder, Colorado, and permission is then sought from parents to review the school

records of both members of each pair for evidence of reading problems. Such evidence includes low reading achievement test scores, referral to resource rooms or reading therapists because of poor reading performance, reports by classroom teachers or school psychologists, and parental interviews (Gillis and DeFries 1989). Pairs of twins in which at least one member has a positive history of a reading problem are then invited to be tested at the University of Colorado where they are administered an extensive test battery that includes the WISC-R (Wechsler 1974) or the WAIS-R (Wechsler 1981) and the Peabody Individual Achievement Test (PIAT; Dunn and Markwardt 1970).

In order to assess the genetic etiology of spelling deficits in the Colorado twin sample, the mean and standard deviation of age-adjusted PIAT Spelling scores of 432 individuals from twin pairs in which neither member of the pair had a positive history of reading problems were first calculated. Pairs of twins were then selected for multiple regression analysis if either member of the pair had a positive history of reading problems, and, in addition, had a spelling score at least one standard deviation below the mean of the controls. Other diagnostic criteria include an IQ score of at least 90 on either the Verbal or Performance Scale of the WISC or WAIS; no diagnosed neurological, emotional, or behavioral problems; and no uncorrected visual or auditory acuity deficits.

Selected items from the Nichols and Bilbro (1966) questionnaire were administered to determine zygosity of same-sex twin pairs. In ambiguous cases, zygosity of the pair was confirmed by analysis of blood samples. The sample of twins ascertained in this manner includes 100 pairs of MZ twins (47 male and 53 female pairs) and 71 pairs of same-sex DZ twins (39 male and 32 female pairs). Subjects ranged in age from 8 to 20 years at the time of testing and all had been reared in English-speaking, middle-class homes.

Subjects in the London twin study were administered a test battery that included the Wechsler Intelligence Scale for Children-Revised (WISC-R; Wechsler 1974), the Neale Analysis of Reading Ability (Neale 1967), and the Schonell Graded Word Reading and Spelling Tests (Schonell and Schonell 1960). The mean and standard deviation of the Schonell Spelling scores of 541 13-year-old children in the London twin sample were computed. Twin pairs in which at least one member of the pair had a spelling score one standard deviation or more below the sample mean and a Verbal or Performance IQ of at least 90 were then selected for multiple regression analysis. Zygosity was assessed using physical similarity criteria and, when necessary, dermatoglyphics and blood-group testing. This sample includes 12 pairs of MZ twins (8 male and 4 female pairs) and 15 pairs of same-sex DZ twins (11 male and 4 female pairs).

Analysis. In order to assess the heritable nature of spelling deficits in the Colorado and London twin studies, the following multiple regression

model was fitted separately to the spelling scores of the twins in the two selected samples:

$$C = B_1P + B_2R + A, \tag{1}$$

where C is the expected cotwin's score, P is the proband's score, R is the coefficient of relationship (R = 1.0 for MZ twins and 0.5 for DZ twins), and A is the regression constant. B_1 is the partial regression of cotwin's score on proband's score, i.e., the weighted average of the separate MZ and DZ cotwin-proband regression coefficients. Thus, B_1 estimates the average regression in this sample for twin pairs without regard to zygosity. B_2, the partial regression of cotwin's score on the coefficient of relationship, equals twice the difference between the means of the MZ and DZ cotwins after covariance adjustment for any difference in the average scores of the MZ and DZ probands. To the extent that the deficit of probands is due to heritable influences, MZ and DZ cotwins will regress differentially to the mean of the unselected population. Therefore, B_2 provides a test of significance for genetic etiology. If each subject's score is expressed as a deviation from the control means prior to regression analysis, B_2 yields a direct estimate of h_g^2. Because truncate selection was employed to ascertain these samples of affected twins, pairs concordant for spelling deficits were double entered for all analyses in a manner analogous to that used for computation of probandwise concordance rates, and standard errors of the resulting regression coefficients were adjusted accordingly (see DeFries, Gillis and Wadsworth, in press).

A pooled estimate of h_g^2 was then obtained by fitting the following extended regression model to data from the two samples simultaneously:

$$C = B_1P + B_2R + B_3S + A, \tag{2}$$

where S is a dummy variable representing sample (+0.5 for each subject in the Colorado sample and −0.5 for the London sample).

In order to test for a differential genetic etiology of spelling deficits in the two samples, the following model was fitted to the combined data sets:

$$C = B_1P + B_2R + B_3S + B_4PS + B_5RS + A, \tag{3}$$

where PS is the product of proband's score and sample, and where RS is the product of relationship and sample. B_4 tests for differential twin resemblance in the two samples, and B_5 tests the significance of the difference between the estimates of h_g^2 obtained from the separate analyses of the two data sets.

In order to assess the possibility of a gender difference in h_g^2 for spelling deficits, equation 2 was fitted separately to data from males and

females in the combined samples. Finally, the significance of this gender difference was tested by fitting the following model to data from both males and females in the combined data set:

$$C = B_1P + B_2R + B_3S + B_4G + B_5PS + B_6PG + B_7RS + B_8RG + B_9SG + A, \quad (4)$$

where G symbolizes gender (coded +0.5 and −0.5 for males and females, respectively). B_4 estimates the differences between the means of male and female probands and B_5, B_6, B_7, B_8 and B_9 provide tests of significance for the indicated interactions. Although additional interaction terms could be included in equations 3 and 4, we focus upon tests of differential genetic etiology as a function of sample (B_5, equation 3) and gender (B_8, equation 4) in this analysis.

RESULTS

The average spelling scores of the MZ and DZ probands and cotwins in the Colorado sample, expressed in standard deviation units from the mean of 432 control subjects, are presented in Table 1. Average spelling scores of selected twins from the London sample, expressed as standard deviations from the mean of 541 individuals that comprised the unselected sample, are also tabulated. From this table it may be seen that the average spelling scores of MZ and DZ probands in the Colorado sample are similar and about two standard deviations below the mean of the matched comparison sample of unaffected twins. In contrast, the average scores of probands in the London sample are somewhat less deviant, and scores of the MZ probands are higher (i.e., less negative) than those of DZ probands. The difference between the average scores of probands in the

Table 1. Mean spelling scores of selected twin pairs tested in the Colorado and London twin studies of reading disability.

Sample		Proband	Cotwin	N_{Pairs}
Colorado[a]	Identical	−2.01	−1.80	100
	Fraternal	−1.92	−1.13	71
London[b]	Identical	−1.29	−0.97	12
	Fraternal	−1.72	−0.77	15

[a] Expressed as standard deviation units from the mean of 432 control individuals in the Colorado Twin Sample.

[b] Expressed as standard deviation units from the mean of 541 individuals in the unselected London Twin Sample.

two samples is presumably due to the difference in diagnostic criteria employed in the two studies. In the Colorado study, a positive school history of reading problems was an additional ascertainment criterion. The difference in average scores of MZ and DZ twins in the London sample has been previously noted by Stevenson et al. (1987). Nevertheless, it may be seen that scores of the DZ cotwins in both samples have regressed more than those of MZ cotwins toward their respective population means. In the Colorado sample, the scores of the DZ cotwins have regressed 0.79 standard deviation units on the average toward the control mean, whereas those of MZ cotwins have regressed only 0.21 standard deviation units. In the London sample, these cotwin-proband differences for DZ and MZ twins are 0.95 and 0.32 standard deviation units, respectively. This differential regression of MZ and DZ cotwin means toward the unselected population mean clearly suggests a substantial genetic etiology for spelling deficits in these two independent studies.

Results of fitting the basic model (equation 1) to the spelling performance data of the Colorado and London twin samples are summarized in Table 2. The estimate of $B_1 = 0.47 \pm 0.10$ obtained from the Colorado sample is a weighted average of the MZ and DZ cotwin-proband regression coefficients for spelling performance, which are 0.61 ± 0.12 and 0.23 ± 0.17, respectively. Corresponding regression coefficients for the selected MZ and DZ twin pairs in the London sample are -0.43 ± 0.70 and -0.03 ± 0.43, respectively, resulting in a B_1 estimate of -0.14. This unexpected negative estimate is almost certainly due in part to the very small number of twin pairs (12 MZ and 15 DZ) with spelling deficits in the London sample. In contrast, the estimates for $B_2 = h_g^2$ obtained from the Colorado and London data sets are remarkably similar, viz., 0.62 ± 0.14 and 0.61 ± 0.39, respectively. These results suggest that over half the spelling performance deficit of probands in the two samples is due to heritable influences.

Table 2. Fit of basic regression model to transformed spelling scores of selected twin pairs tested in the Colorado and London twin studies of reading disability

Sample	Coefficient	Estimate ± S.E.	t	p[a]
Colorado	B_1	0.47 ± 0.10	4.70	<0.001
	$B_2 = h_g^2$	0.62 ± 0.14	4.43	<0.001
London	B_1	−0.14 ± 0.36	−0.39	<0.35
	$B_2 = h_g^2$	0.61 ± 0.39	1.57	<0.06
Combined	B_1	0.42 ± 0.10	4.29	<0.001
	$B_2 = h_g^2$	0.62 ± 0.13	4.68	<0.001

[a] One-tailed.

Pooled estimates of B_1 and B_2 obtained when equation 2 was fitted simultaneously to the two data sets are also presented in Table 2. As expected, given the difference in sample size between the two data sets, the parameter estimates obtained from the combined data are highly similar to those from the Colorado study.

Although there is obviously no evidence for a differential genetic etiology of spelling deficits in the Colorado and London data sets (0.62 and 0.61, respectively), equation 3 was nonetheless fitted to data from the combined samples to test this hypothesis explicitly. As expected, the regression coefficient that provides a test of the magnitude of this interaction is nonsignificant ($B_5 = 0.003 \pm 0.384$, $t = 0.01$, $p > 0.99$, two-tailed). Because sample was coded +0.5 and −0.5 for the Colorado and London data sets, this coefficient exactly equals the difference between the two h_g^2 estimates, i.e., $0.6165 - 0.6131 = 0.0034$. In contrast to the test for the difference between the two estimates of h_g^2, the regression coefficient that assesses differential twin resemblance in the two samples approaches statistical significance ($B_4 = 0.61 \pm 0.35$, $t = 1.77$, $p < 0.08$, two-tailed).

Estimates of h_g^2 obtained by fitting equation 2 separately to transformed spelling data from male and female twin pairs included in the combined data set are presented in Table 3. The resulting estimate of h_g^2 for males (0.66 ± 0.18, $p < 0.001$, one-tailed) is larger than that for females (0.56 ± 0.19, $p < 0.003$), suggesting that genetic factors may be somewhat more important as a cause of spelling deficits in males than in females. However, the coefficient that tests for differential genetic etiology in males and females ($B_8 = 0.10 \pm 0.27$, $p > 0.50$, two-tailed) is not significant.

DISCUSSION

DeFries and Fulker (1985, 1988) have noted that a multiple regression analysis of continuous data from selected twin pairs provides a more

Table 3. Estimates of group heritability of spelling deficits for males and females in the combined Colorado and London data sets

Gender	Number of twin pairs		$B_2 = h_g^2$	p[a]
	MZ	DZ		
Males	55	50	0.66 ± 0.18	<0.001
Females	57	36	0.56 ± 0.19	<0.003

[a] One-tailed.

general and flexible test of genetic etiology than does the comparison of concordance rates employed in previous twin studies (Zerbin-Rüdin 1967, Bakwin 1973, Stevenson et al. 1984, 1987). When probands are identified because of deviant scores on a continuous variable such as reading or spelling performance, genetic factors are implicated if the MZ and DZ cotwin scores regress differentially toward the mean of the unselected population. The partial regression of cotwin's score on the coefficient of relationship (equation 1) estimates twice the difference between the MZ and DZ cotwin means after covariance adjustment for any difference between the MZ and DZ proband means. When each score is transformed by expressing it as a deviation from the mean of the unselected population and dividing by the difference between the proband and control means, this regression coefficient directly estimates h_g^2, an index of the extent to which the deficit of probands is due to heritable influences.

In order to increase the number of twin pairs available for multiple regression analysis, we have combined data collected in the Colorado Reading Project and the London Twin Study. Due to differences between the measures obtained in the Colorado and London studies, the current analyses focus specifically on spelling performance. When equation 1 was fitted to transformed spelling scores from selected MZ and DZ twin pairs in the Colorado and London samples, resulting estimates of h_g^2 were 0.62 $\pm$ 0.14 and 0.61 $\pm$ 0.39, respectively, suggesting that over half of the deficit in the spelling performance of probands is due to heritable influences in both samples. The similarity between these h_g^2 estimates is remarkable, given the differences between the two studies. Subjects in the Colorado study are administered a test of spelling recognition, whereas subjects in the London study were required to generate correct spellings of individual words. Moreover, different ascertainment criteria were employed to select probands in the two studies. That similar h_g^2 estimates were obtained in these two independent twin studies strengthens the evidence for a substantial genetic etiology of spelling deficits. These estimates of h_g^2 for spelling are somewhat higher than that for a composite measure of reading performance (0.50) estimated from data of the Colorado study (DeFries and Gillis 1991), thus supporting the suggestion of Stevenson et al. (1984) that spelling may be less susceptible than reading to environmental influences.

Multiple regression analysis was also used to test the hypothesis that the cause or causes of spelling disability may differ in males and females. When equation 2 was fitted separately to spelling data from male and female twin pairs in the combined data set, resulting estimates of h_g^2 were 0.66 $\pm$ 0.18 and 0.56 $\pm$ 0.19, respectively, a nonsignificant difference. Nonetheless, it is interesting to note that the gender difference in estimates of h_g^2 for spelling is opposite that found for a composite measure of reading performance in the Colorado Reading Project (DeFries, Gillis and

Wadsworth, in press). Although the difference in estimates of h_g^2 for reading performance of males and females (0.42 and 0.48, respectively) was also nonsignificant, this differential pattern of results is consistent with the hypothesis of a developmental dissociation between reading and spelling deficits in learning-disabled children (Stevenson et al. 1987, Wadsworth et al. 1989).

The test of genetic etiology provided by the multiple regression analysis of selected twin data is also statistically powerful (DeFries and Fulker 1988). For example, when equation 1 was recently fitted to transformed discriminant function data from the Colorado sample of reading-disabled probands and cotwins (DeFries, Olson, Pennington and Smith 1991), the squared multiple correlation was 0.26 and the correlation between proband and cotwin scores was 0.43. Thus, the power (Cohen 1977) to detect a significant B_2 at the 0.05 level (one-tailed test) in a sample of 100 pairs of MZ and 100 pairs of DZ twins is 0.99. This power of the multiple regression analysis of selected twin data is clearly demonstrated in the present analysis of data from the London twin sample (only 12 pairs of MZ twins and 15 pairs of DZ twins) in which the estimate of h_g^2 is marginally significant ($p < 0.06$, one-tailed).

Because the multiple regression test for genetic etiology is statistically powerful, the test for differential genetic etiology is also relatively powerful. For example, if h_g^2 in males and females differed by 0.5, the power to detect a significant interaction between zygosity and gender at the 0.05 level (two-tailed test) in a sample of 100 pairs of MZ and 100 pairs of DZ twins would be about 0.75 (DeFries and Fulker 1988). However, if the difference in h_g^2 were 0.3, the power would be only about 0.30. By increasing the sample size to 150 pairs of MZ twins and 150 pairs of DZ twins, the power would be increased to about 0.90 and 0.50 in these two cases. Thus, a larger sample of twins will be required to test more rigorously the hypothesis that the etiology of spelling deficits differs as a function of group membership.

Twin studies of reading disability are relatively easy to initiate, and small studies could be readily accomplished even by research groups with limited resources. Results of such twin studies could be individually informative; moreover, collaborative analyses of combined data sets from such studies could facilitate statistically powerful tests of hypotheses that are relevant to several current issues in the field of reading disability (DeFries and Gillis 1991).

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