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The Practical Effect of Routine Data Transformations on Absolute EEG Power Derived from Spectral Analysis

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This investigation was conducted to evaluate the effects of selected EEG data transformations on analysis of variance (ANOVA) results in a repeated measures design. Eighteen subjects were given resting EEG evaluations at 8 different times during a period of continuous wakefulness. Following spectral analysis, the data were either analyzed as untransformed absolute EEG power, log-natural transformed power, or 2-arcsine-square root transformed relative power. Results indicated that while the relative power transformation lead to a more sensitive statistical analysis, it concurrently introduced data interpretation problems. In contrast, the results with both untransformed and transformed absolute power were quite similar. Overall, it was concluded that although transformations improve the Gaussian properties of the data, they do not appear to substantially impact the conclusions that will be drawn from a repeated measures ANOVA.

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Introduction

Although research indicates the human EEG possesses Gaussian properties (Bender et al., 1992), the results of spectral analysis of these data often are not normally distributed. This has led to the recommendation that log or other transformations be applied (Gasser, Bächer, and Möchs, 1982) since many statistical techniques including analysis of variance (ANOVA) rely on normal distributions (Hayes, 1973). Gasser, Bächer, and Möchs (1982) reported that broad band spectral EEG parameters from healthy volunteers often depart substantially from normality. They recommended that appropriate transformations can minimize problems associated with the scale of measurement and the underlying mechanisms responsible for the EEG. Specifically, these authors reported the application of log transformations substantially reduced departures from normality in absolute power data (except in the beta band) and arcsine-square-root transformations significantly improved the behavior of relative power data (although a log(x/(1-x)) transformation was even better). However, although the authors thoroughly addressed the issue of the effects of transformations on normality versus non-normality, they did not indicate the extent to which the transformations would lead to divergent conclusions about the effects of independent variables after statistical analysis. Since ANOVA is known to be robust to violations of the normality assumption (Kirk, 1968), a determination of the impact of two of the recommended transformations on the number of statistically-significant effects resulting from a 2-way ANOVA of the same data (transformed versus non-transformed) was of interest.

Methods

Eighteen male subjects between the ages of 22 and 31 (mean=24.4) were tested to examine the difference in EEG as a function of sleep deprivation. Subjects were continuously deprived of sleep for 38 hours. EEG data from 7 electrode sites (Fz, C3, Cz, C4, Pz, O1, and O2) were collected using a standard Cadwell Spectrum 32. Subjects were tested at 1030, 1430, and 1830 on pre-deprivation days and at 0230, 0630, 1030, 1430, and 1830 on deprivation days. During each EEG session, subjects were asked to remain still and quiet with eyes open for 1.5 minutes followed by 1.5 minutes of eyes closed. Spectral analyses were performed on three artifact-free epochs of eyes open and eyes closed EEG for each subject. The activity bands were delta (1.0-3.0 Hz), theta (3.0-8.0 Hz), alpha (8.0-13.0 Hz), and beta (13.0-20.0 Hz). The average absolute power within each of these bands was analyzed separately as: 1) untransformed absolute power data, 2) log-natural-transformed absolute power, and 3) arcsine-square-root transformed relative power. Each of the activity bands for the three sets of data was analyzed with repeated measures ANOVAS for time (1030, 1430, 1830, 0230, 0630, 1030, 1430, 1830) and eyes (eyes open and eyes closed). Thus, there were four analyses (delta, theta, alpha, and beta) conducted on each data set (untransformed, log transformed, and arcsine-square-root transformed). This permitted an evaluation of whether the number of significant effects was altered as a function of the transformations. In addition, a description of the skewness and kurtosis of the transformed variables permitted an examination of how normality was affected.

Results

Delta activity

Absolute Power

The ANOVA on delta activity indicated a time-by-eyes effect at O2 ($F(7,119)=3.80$, $p=.0009$) which was due to differences in the amount of delta activity recorded across the testing times under eyes closed but not eyes open. Follow-up contrasts indicated there was more delta recorded at B1030, B1430 and D1830 when compared to D0230, D0630 and D1030 (see figure 1). There were main effects on the time factor at C3 ($F(7,119)=2.44$, $p=.0224$) and C4 ($F(7, 119)=2.19$, $p=.0400$). These effects were primarily due to more delta recorded during the D1830 testing time than the B1430, B1830, D0230, and D0630 times. For electrode C4, there was more delta at D1430 than D0230 (see table 1). There were eyes main effects at C3 ($F(1,17)=53.80$, $p=.0001$), C4 ($F(1,17)=33.78$, $p=.0001$), Cz ($F(1,17)=20.54$, $p=.0003$), Fz ($F(1,17)=27.73$, $p=.0001$), O1 ($F(1,17)=17.02$, $p=.0007$), O2 ($F(1,17)=32.95$, $p=.0001$), and Pz ($F(1,17)=42.51$, $p=.0001$). These were all due to increases in delta power under eyes closed when compared to eyes open.

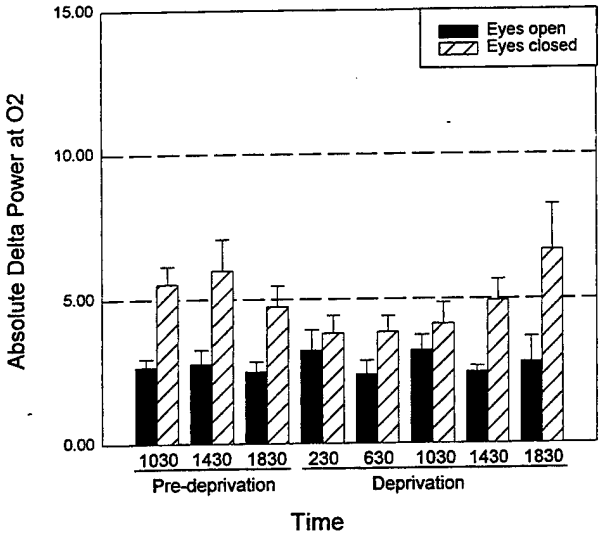

Figure 1. Effects of testing time and eye closure on untransformed absolute delta activity at O2.

Log Natural Transformed Power

The ANOVA on delta activity indicated time-by-eyes effects at Fz ($F(7,119)=2.06$, $p=.0530$) and O2 ($F(7, 119)=4.01$, $p=.0006$). These effects were due to differences in the amount of delta

activity recorded under eyes closed but not eyes open. Contrasts showed there was more delta recorded at D1830 than B1030, B1430, D0230 and D0630 for electrode Fz. For Fz, there was also more delta at B1830 than the other baseline times while D0230 showed a decrease in delta from the D1030 and B1830 times. For electrode O2, there was more delta recorded at D1830 than D0230, D0630, or D1030. There was also less delta recorded at D0230 than any of the baseline times. The B1030 testing time for O2 showed more delta than the D0230, D0630, and D1030 times, and there was more delta at B1430 than D1030 (see figure 2). There were time main effects at C3 ($F(7,119)=2.49$, $p=.0201$), C4 ($F(7,119)=2.32$, $p=.0297$), and Fz ($F(7,119)=2.32$, $p=.0299$). These were due primarily to more delta recorded at D1830 than the other testing times for each of the electrodes (however, there were exceptions). For electrode Fz, there was also less delta at B1430 and D0230 than B1830. For C3, contrasts indicated there was more delta at D1030 than any of the remaining testing times (except D1830). There was less delta for C3 at D0630 than D1430. Electrode C4 showed less delta at B1830 than D1030 and less delta at D0230 than D1430 (see table 1). There were also eyes main effects at C3 ($F(1,17)=95.55$, $p=.0001$), C4 ($F(1,17)=57.31$, $p=.0001$), Cz ($F(1,17)=57.27$, $p=.0001$), Fz ($F(1,17)=92.86$, $p=.0001$), O1 ($F(1,17)=44.67$, $p=.0001$), O2 ($F(1,17)=63.12$, $p=.0001$), and Pz ($F(1,17)=62.81$, $p=.0001$). These were due to increased delta activity under eyes closed compared to eyes open.

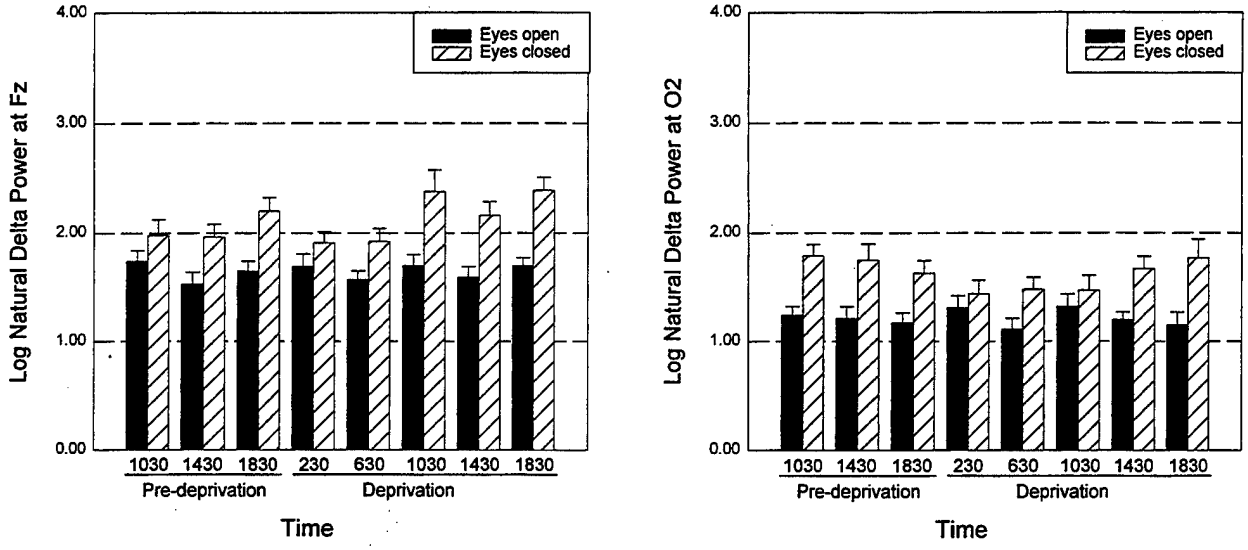

Figure 2. Effects of testing time and eye closure on log-natural transformed absolute delta activity at Fz and O2.

Transformed Relative Power

The ANOVA on delta activity indicated time-by-eyes effects at O1 ($F(7,119)=3.84$, $p=.0009$) and O2 ($F(7,119)=4.87$, $p=.0001$). The effects at O1 were due to more relative delta recorded under eyes open than eyes closed, especially at D0230, although there were no overall time effects under either condition. The effects at O2 were due to differences in the amount of delta activity

under eyes open but not eyes closed. There was more delta recorded at D0230 than any of the baseline times or D1430 and D1830. Contrasts indicated there was less delta recorded at B1830 than many of the deprivation times for O2. In addition, less delta was recorded at D1830 than D0230 or D1030 (see figure 3). There were no overall time main effects. However, there were eyes main effects at all electrode sites: C3 ($F(1,17)=66.74$, $p=.0001$), C4 ($F(1,17)=64.89$, $p=.0001$), Cz ($F(1,17)=68.54$, $p=.0001$), Fz ($F(1,17)=59.68$, $p=.0001$), O1 ($F(1,17)=83.11$,

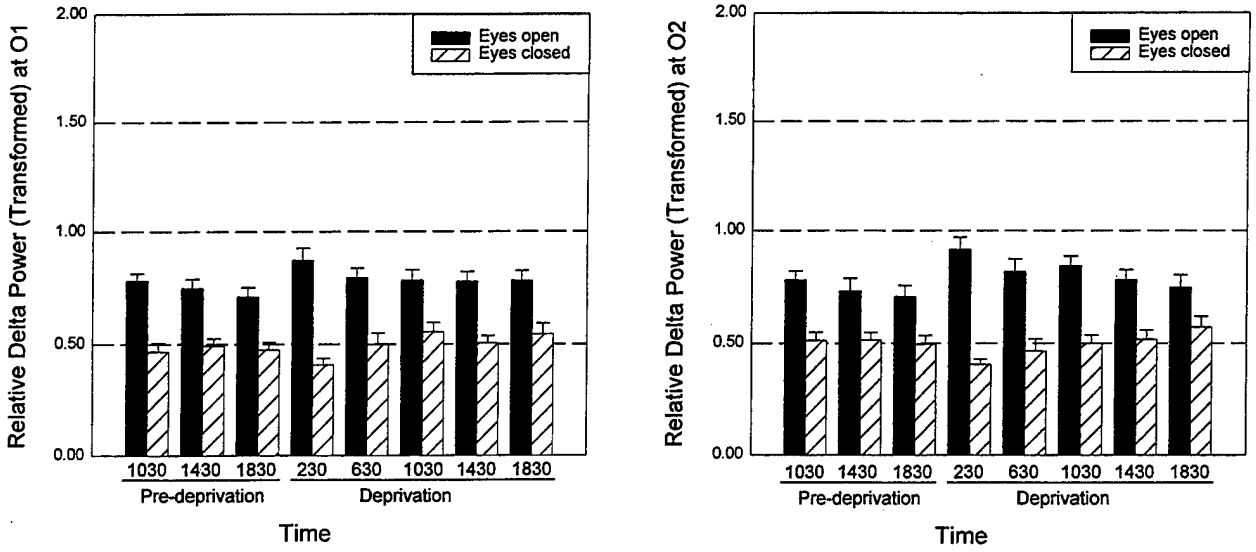

Figure 3. Effects of testing time and eye closure on transformed relative delta activity at O1 and O2.

Table 1.
Mean delta activity at each testing time.

Data Type	Electrode	B1030	B1430	B1830	D0230	D0630	D1030	D1430	D1830
Absolute	C3	4.12	4.11	4.21	4.01	3.83	6.35	5.41	5.45
Power	C4	4.45	4.28	4.13	3.78	4.74	6.63	5.63	6.01
	Fz	6.77	5.63	7.14	5.83	5.35	10.0	6.70	7.99
Log	C3	1.55	1.50	1.56	1.54	1.48	1.73	1.69	1.74
Power	C4	1.57	1.56	1.52	1.51	1.65	1.75	1.74	1.80
	Fz	1.86	1.75	1.93	1.80	1.74	2.04	1.88	2.04
Relative	C3	0.69	0.65	0.69	0.71	0.68	0.74	0.71	0.74
Power	C4	0.70	0.71	0.67	0.71	0.73	0.77	0.72	0.75
	Fz	0.77	0.70	0.78	0.76	0.71	0.82	0.73	0.78

$p=.0001$), O2 ($F(1,17)=69.78$, $p=.0001$), and Pz ($F(1,17)=117.37$, $p=.0001$). These effects were due to more delta activity under eyes open than eyes closed.

Absolute Power

The ANOVA on theta power indicated time-by-eyes effects at Cz ($F(7,119)=2.20$, $p=.0393$), Fz ($F(7,119)=2.44$, $p=.0224$), and O2 ($F(7,119)=2.08$, $p=.0503$), due to differences in the amount of theta activity under eyes closed but not eyes open. Contrasts showed there was more theta recorded at D1830 than at B1830 or D0230 for Cz. Cz also showed more theta at B1030 than D0230 and substantially more theta at D1030 than B1830 or D0230. At Fz, contrasts indicated more theta recorded at D1030 than several of the other testing times. At O2, there was more theta at D1030 than B1830 or D0230. There was also more theta at D0630 than D0230. In addition, there was more theta at B1030 than B1430 (see figure 4). Time main effects were observed at Cz ($F(7,119)=2.41$, $p=.0241$), Fz ($F(7,119)=3.12$, $p=.0047$), and O2 ($F(7,119)=2.19$, $p=.0398$). The effects at Cz were due to less theta activity at D0230 than any of the remaining deprivation times. There was also less theta at B1830 than D1030 or D1830 for Cz. The time effects at Fz were mainly due to more theta recorded at D1030 and D1830 than the remaining testing times, though there was also less theta at D0230 than D0630, D1030, or D1830. The effects at O2 were due to less theta recorded at D0230 than the remaining deprivation testing times and B1030 (see table 2). There were eyes main effects at C3 ($F(1,17)=45.22$, $p=.0001$), C4 ($F(1,17)=37.78$, $p=.0001$), Cz ($F(1,17)=49.95$, $p=.0001$), Fz ($F(1,17)=32.69$, $p=.0001$), O1 ($F(1,17)=22.92$, $p=.0002$), O2 ($F(1,17)=15.55$, $p=.0010$), and Pz ($F(1,17)=27.69$, $p=.0001$). These were due to increases in theta activity during eyes closed in comparison to eyes open.

Log Natural Transformed Power

The ANOVA on theta activity indicated time-by-eyes effects at Cz ($F(7,119)=2.09$, $p=.0495$) and O2 ($F(7,119)=2.49$, $p=.0199$) due to differences in theta during eyes closed but not eyes open. The effects at Cz were because of more theta at D1830 than B1030, B1830, and D0230. The effects at Cz also were attributable to less theta at D0230 than at most of the remaining deprivation times. In addition, there was less theta at B1830 than D1030 or D1830 (see figure 5). The effects at O2 were mainly due to less theta recorded at D0230 than the remaining deprivation times, and at B1030 and B1430. The presence of more theta was detected at B1030 than B1830 or D0230 for O2. Contrasts for O2 also showed there was more theta at D1030 than B1830 or D0230. There were time main effects at C3 ($F(7,119)=3.96$, $p=.0006$), C4 ($F(7,119)=3.63$, $p=.0014$), Cz ($F(7,119)=3.09$, $p=.0050$), Fz ($F(7,119)=4.78$, $p=.0001$), and Pz ($F(7,119)=2.47$, $p=.0211$). These effects were mainly due to more theta recorded at D1830 than the majority of the remaining testing times at C3, C4, and Fz. Cz showed more theta at D1830 than B1030, B1830, and D0230. Contrasts at C3 indicated there was more theta at D1030 than most of the remaining testing times (see table 2). Less theta was detected at D0230 when compared to the other times for each electrode. At electrodes C4 and Cz, there was less theta at D0230 than the remaining deprivation times and at B1430. Cz also had less theta at D0230 than B1030. Electrode Fz showed more theta being recorded at D1030 than the majority of the testing times. Generally, for Fz there also was more theta recorded at D0630 than the other testing times

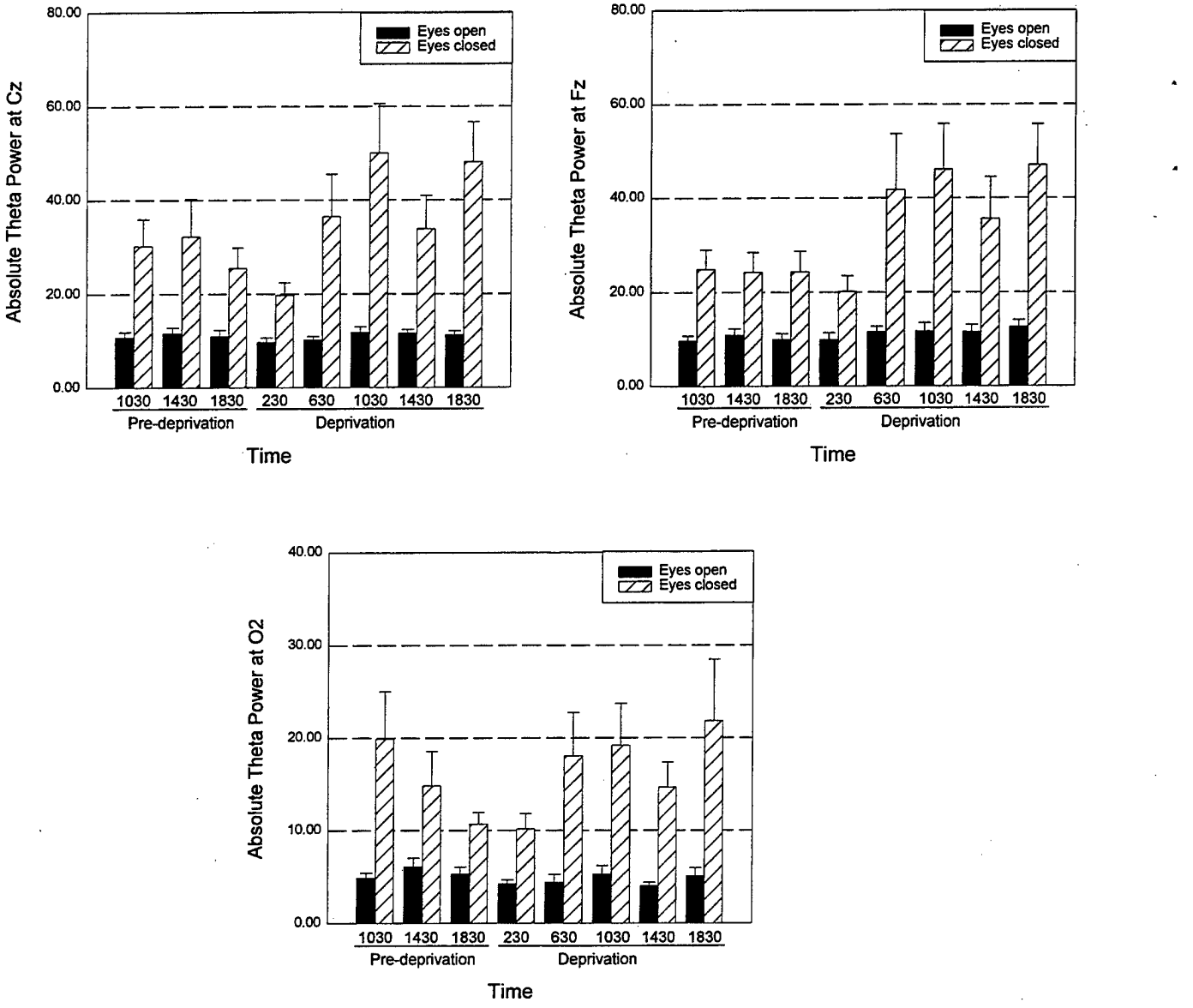

Figure 4. Effects of testing time and eye closure on untransformed absolute theta power at Cz, Fz, and O2.

and less theta at D0230 than any of the other deprivation times. At Pz, there was less theta at D0230 than several of the remaining deprivation testing times and B1430. There were eyes main effects at C3 ($F(1,17)=107.23$, $p=.0001$), C4 ($F(1,17)=111.00$, $p=.0001$), Cz ($F(1,17)=124.79$, $p=.0001$), Fz ($F(1,17)=104.60$, $p=.0001$), O1 ($F(1,17)=81.58$, $p=.0001$), O2 ($F(1,17)=85.12$, $p=.0001$), and Pz ($F(1,17)=103.06$, $p=.0001$). These were due to increases in theta during eyes closed in comparison to eyes open.

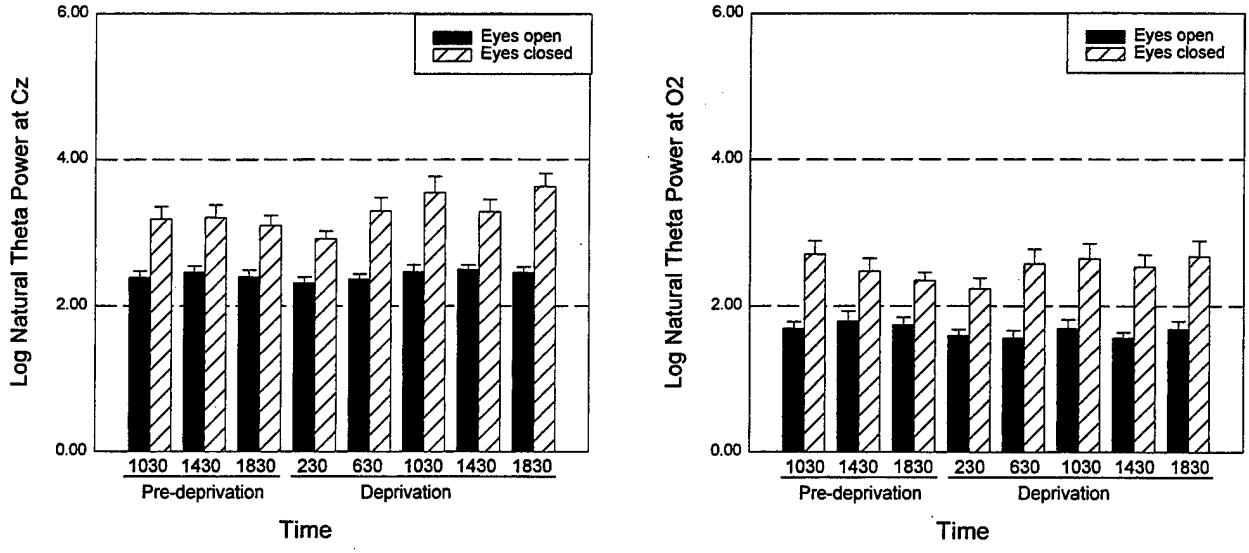

Figure 5. Effects of time of testing and eye closure on log-natural transformed theta activity at Cz and O2.

Transformed Relative Power

The ANOVA on theta activity indicated time-by-eyes effects at C3 ($F(7,119)=2.44$, $p=.0224$), Cz ($F(7,119)=2.18$, $p=.0402$), Fz ($F(7,119)=2.41$, $p=.0242$), O1 ($F(7,119)=2.57$, $p=.0170$), and O2 ($F(7,119)=4.07$, $p=.0005$) which were due to differences in the amount of theta activity recorded at various times of day under eyes closed but not eyes open. Contrasts showed these effects were predominantly due to more theta recorded at D1830 for C3, Cz, and Fz, and more theta at D1030 at each electrode. O1, O2, and Fz showed more theta at D1830 than D0230. O2 and O1 also showed more theta at D1830 than B1830. O1 had more theta at D1830 than B1030. There was less theta recorded at D0230 than most of the other testing times, and, generally, more theta was recorded at D0630 than at D0230 for each electrode. Electrode Fz had more theta at D0630 than B1830 and B1030. At electrodes C3, Cz, and O2 there was more theta at D1030 than at D1430 (see figure 6). There were time main effects at C3 ($F(7,119)=3.96$, $p=.0006$), C4 ($F(7,119)=3.30$, $p=.0031$), Cz ($F(7,119)=3.28$, $p=.0032$), Fz ($F(7,119)=6.62$, $p=.000$), O1 ($F(7,119)=3.08$, $p=.0051$), O2 ($F(7,119)=2.42$, $p=.0235$), and Pz ($F(7,119)=3.04$, $p=.0056$). Follow-up contrasts indicated more theta at D1830 than the majority of the other times for C3, C4, and Fz. Cz and O1 had more theta at D1830 than B1030, B1830, or D0230. There was more theta at D1030 than the majority of the times for C3, Cz, Fz, O1, O2, and Pz. C4 had more theta at D1030 than B1830 or D0230 (see table 2). In addition, there was less theta at D0230 than most of the other testing times for each electrode. At several electrodes, contrasts showed more theta at D1030 than D1430. There were eyes main effects at C3 ($F(1,17)=7.22$, $p=.0156$), C4 ($F(1,17)=5.02$, $p=.0387$), Cz ($F(1,17)=11.76$, $p=.0032$), Fz ($F(1,17)=7.70$,

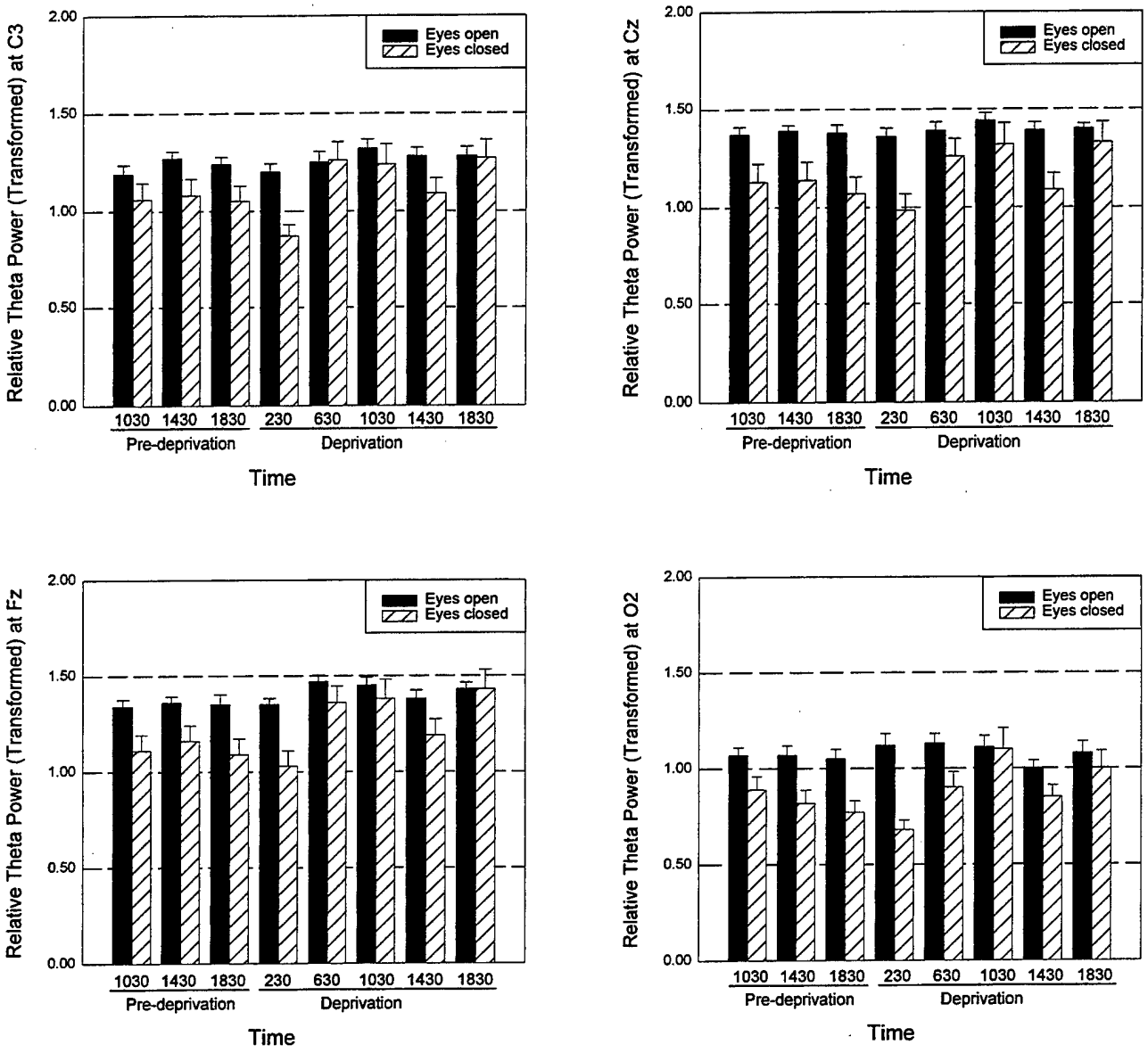

Figure 6. Effects of testing time and eye closure on transformed relative theta power at C3, Cz, Fz, and O2.

p=.0130), O1 (F(1,17)=38.12, p=.0001), O2 (F(1,17)=31.27, p=.0001), and Pz (F(1,17)=14.47, p=.0014). These effects were due to differences in the amount of theta activity between eyes open and eyes closed (greater relative theta under eyes open).

Alpha Activity

Absolute Power

The ANOVA on alpha power indicated time-by-eyes effects at C3 ($F(7,119)=3.25$, $p=.0034$), C4 ($F(7,119)=2.16$, $p=.0421$), Cz ($F(7,119)=2.23$, $p=.0364$), Fz ($F(7,119)=2.05$, $p=.0546$), O1 ($F(7,119)=3.68$, $p=.0012$), O2 ($F(7,119)=2.87$, $p=.0083$), and Pz ($F(7,119)=2.64$, $p=.0144$). These effects were due to differences in the amount of alpha activity for eyes closed at C3, C4, Cz, O1, O2, and Pz (the effect for Fz was marginal at $p=.0654$). Electrode O2 also showed differences under eyes open. Contrasts for the effects at eyes closed showed a trend for less alpha at D0630 than many of the other times at C3, C4, Cz, O2, and Pz, and contrasts at O1 showed less alpha at D0630 compared to D0230. Also, at O1 and O2, alpha tended to be lower at D1830 than elsewhere. At C3, Cz, O2, and Pz, alpha was greater at D0230 than D1830. At O2, there was a decrease from D0630 to D1830, and at O1, alpha was lower at D1030 than most other

Table 2.
Mean theta activity at each testing time.

Data type	Electrode	B1030	B1430	B1830	D0230	D0630	D1030	D1430	D1830
Absolute Power	Fz	17.33	17.60	17.15	15.09	26.68	28.92	23.60	29.86
	C3	12.94	14.78	12.48	9.03	17.50	18.20	15.70	17.33
	C4	14.31	14.70	12.95	9.91	17.82	19.24	14.91	19.89
	Cz	20.46	21.92	18.23	14.71	23.31	30.87	22.72	29.65
	Pz	19.67	20.94	14.72	12.15	18.33	23.12	17.59	21.79
	O1	10.56	10.73	8.38	8.29	10.89	13.06	9.60	13.10
	O2	12.36	10.45	7.98	7.18	11.20	12.21	9.33	13.44
Log Power	Fz	2.67	2.71	2.66	2.60	2.91	2.97	2.85	3.05
	C3	2.38	2.48	2.37	2.18	2.48	2.61	2.56	2.61
	C4	2.42	2.45	2.37	2.24	2.53	2.62	2.52	2.70
	Cz	2.79	2.84	2.75	2.62	2.84	3.01	2.90	3.04
	Pz	2.60	2.69	2.52	2.41	2.58	2.74	2.65	2.75
	O1	2.11	2.14	2.03	1.98	2.05	2.20	2.13	2.21
	O2	2.20	2.14	2.04	1.91	2.07	2.17	2.05	2.18
Relative Power	Fz	1.23	1.26	1.22	1.19	1.41	1.41	1.29	1.43
	C3	1.13	1.17	1.15	1.03	1.26	1.28	1.19	1.27
	C4	1.18	1.22	1.14	1.10	1.24	1.30	1.14	1.30
	Cz	1.25	1.26	1.23	1.17	1.33	1.38	1.24	1.37
	Pz	1.06	1.06	1.03	0.97	1.13	1.21	1.04	1.14
	O1	0.93	0.95	0.91	0.89	1.03	1.14	0.94	1.07
	O2	0.98	0.95	0.91	0.90	1.02	1.11	0.93	1.00

times. C3, Cz, O2, and Pz showed a decrease in alpha from D0230 to D1030. O2 also showed more alpha at B1830 than D1030. At C3, there was an increase from B1830 to D0230. At C4, alpha was greater at D1430 than D0630 or D1030. At Cz, there was more alpha at D1430 than D1030. O1 indicated an increase at D0230 from the B1830 testing time. The eyes open effect at O2 was due to less alpha at D0230 than the baseline times (see figure 7). There were time main effects at C4 ($F(7,119)=2.07$, $p=.0517$), Cz ($F(7,119)=2.29$, $p=.0321$), O1 ($F(7,119)=3.00$, $p=.0062$), and Pz ($F(7,119)=2.35$, $p=.0276$). At C4, there was more alpha at B1830 than D0630 and D1030, and more alpha at D1430 than D1030. At Cz, there also was more alpha at B1830 than at D0630 and more alpha at D0230 than at D0630 or D1030. Alpha tended to increase from D1030 to D1430 for Cz. At O1, there was less alpha at D1830 than at B1030, B1830, and D0230. D1030 showed a trend for less alpha at O1 while D0230 indicated more alpha compared to the other testing times. At Pz, alpha was lower at D0630 compared to the other times, while it was higher at D0230 (see table 3). There were eyes main effects at C3 ($F(1,17)=40.18$, $p.=.0001$), C4 ($F(1,17)=45.91$, $p=.0001$), Cz ($F(1,17)=39.01$, $p=.0001$), Fz ($F(1,17)=41.30$, $p=.0001$), O1 ($F(1,17)=41.06$, $p=.0001$), O2 ($F(1,17)=50.81$, $p=.0001$), and Pz ($F(1,17)=47.33$, $p=.0001$). These were due to substantial increases in alpha activity at eyes closed in comparison to eyes open.

Log Natural Transformed Power

The ANOVA on alpha activity indicated time-by-eyes effects at C3 ($F(7,119)=2.28$, $p=.0328$), O1 ($F(7,119)=4.73$, $p=.0001$), O2 ($F(7,119)=4.85$, $p=.0001$), Pz ($F(7,119)=2.36$, $p=.0271$), and Fz ($F(7,119)=2.84$, $p=.0090$). The effects were due to differences in the amount of alpha recorded across the different testing times under eyes closed for each electrode. Also, at electrodes O1 and O2, there were differences under eyes open. Contrasts indicated a trend for less alpha at D0630 compared to the other times under eyes closed at every electrode except O2, which showed less alpha at D0630 compared to D0230. At C3, O1, O2, and Fz, there was a trend towards less alpha at D1030 than at most of the other times. At Pz, there was less alpha at D1030 compared to D0230 and B1430. For C3, there was less alpha at D1030 than D1830, and at O1 the comparison between D1830 and D0230 was significant (less alpha at D1830). For electrodes C3 and O1, there was more alpha at D0230 than B1830. O1 also showed more alpha at D0230 than B1430 under eyes closed. At C3, O1, and Fz, more alpha was detected at D1430 compared to D1030 (see figure 8). The contrasts for eyes open at O1 and O2 showed less alpha at D0230 and D0630 than at the other testing times. At O2 there also was more alpha at D1830 and D1430 compared to D0230 and D0630. O2 also showed more alpha at B1430 than most deprivation times. There were time main effects at Fz ($F(7,119)=2.03$, $p=.0573$), O1 ($F(7,119)=2.50$, $p=.0198$), and O2 ($F(7,119)=2.06$, $p=.0526$). These effects were due to a trend towards decreased alpha at D1030 in comparison to the other times for Fz and O1. At O2, there was less alpha at D1030 than B1830 and B1430. Also, at O1 and O2, there was a trend towards less alpha at D0630 than most of the other times. There was also an increase at D1430 when compared to D1030 at Fz and O1 (see table 3). Eyes main effects were located at C3 ($F(1,17)=146.30$, $p=.0001$), C4 ($F(1,17)=133.31$, $p=.0001$), Cz ($F(1,17)=130.41$, $p=.0001$), Fz ($F(1,17)=121.60$, $p=.0001$), O1 ($F(1,17)=279.74$, $p=.0001$), O2 ($F(1,17)=239.22$, $p=.0001$), and

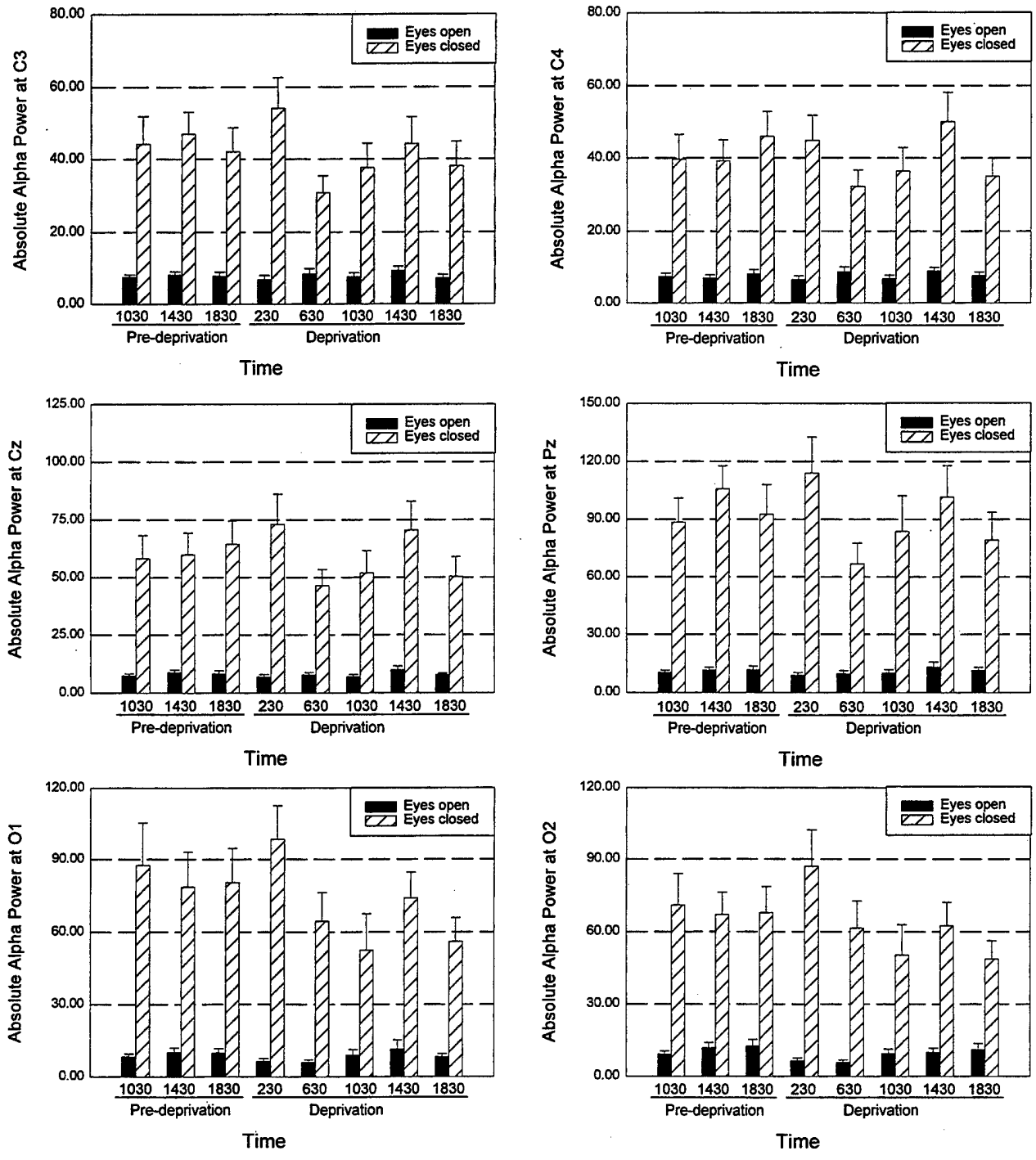

Figure 7. The effects of testing time and eye closure on untransformed absolute alpha activity at several electrodes.

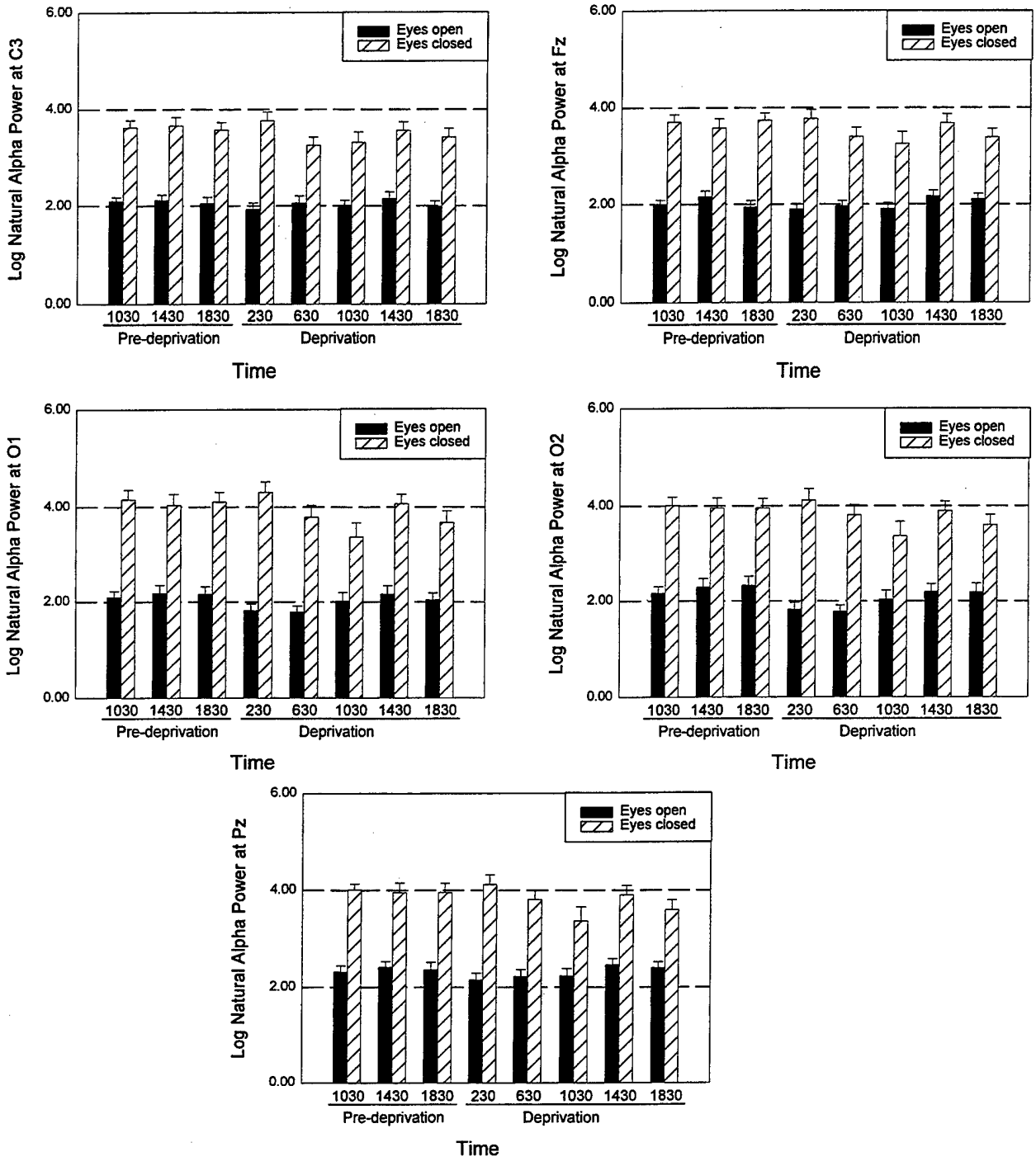

Figure 8. Effects of testing time and eye closure on log-natural transformed alpha activity at several electrodes.

Pz (F(1,17)=204.78, p=.0001). These were due to increases in alpha activity during eyes closed in comparison to eyes open.

Transformed Relative Power

The ANOVA on alpha activity indicated time-by-eyes effects at C3 (F(7,119)=3.09, p=.0049), Cz (F(7,119)=2.97, p=.0066), Fz (F(7,119)=4.27, p=.0003), O1 (F(7,119)=4.63, p=.0001), O2 (F(7,119)=5.51, p=.0001), and Pz (F(7,119)=2.90, p=.0078). These effects were due to differences in the amount of alpha activity at eyes closed for all electrodes. At electrode O2, there were differences under eyes open as well. Contrasts for eyes closed effects showed a trend toward less alpha at D1030 than elsewhere. At C3 and Fz, there was less alpha at D1830 than at other times. At Cz, there was less alpha at D1830 than at B1030, B1830, or D0230. At O1, there was less alpha at D1830 than D0230 or B1030. O2 showed less alpha at D1830 than at B1430, B1830 or D0230. There was an increase in alpha at D0230 for most electrodes. At electrodes C3 and Fz, there was a tendency towards less alpha at D0630 and less alpha at D1030 than D1430. At O1 and O2, there was more alpha at D1430 than D1030. At O2, for eyes open, there was a decrease in alpha at D0230 when compared to the baseline times. There was an increase in alpha for O2 at B1830 compared to D0230 and D0630 for eyes open. In addition, there was more alpha at D1430 than D0230 or D1030 (see figure 9). There were time main effects at C3 (F(7,119)=2.33, p=.0287), C4 (F(7,119)=2.62, p=.0149), Cz (F(7,119)=2.46, p=.0218), Fz (F(7,119)=4.44, p=.0002), O1 (F(7,119)=2.24, p=.0356), and O2 (F(7,119)=2.05, p=.0542). Follow-up contrasts showed a trend toward less alpha activity at D1030 when compared with the other testing times, though O2 showed less alpha at only D1030 compared to B1830 and B1430. For C3 and Fz, there was a decrease in alpha at the D1830 testing time. For Fz, there was a trend for less alpha at D0630 than elsewhere. C3 and C4 showed less alpha at D0630 compared to D0230. C4 and O2 also showed less alpha at D0630 than at B1830. C4 and Cz showed less alpha at D1830 than B1830. C4 indicated less alpha at D1830 than B1430 while Cz showed less alpha at D1830 than D0230. Generally, there was more alpha at D0230 than at the other times for most of the electrodes tested, though at O1, the only significant comparison was between D0230 and D1030. At every electrode, there was an increase in alpha at D1430 when compared with D1030 (see table 3). There were eyes main effects at C3 (F(1,17)=41.37, p=.0001), C4 (F(1,17)=28.95, p=.0001), Cz (F(1,17)=41.34, p=.0001), Fz (F(1,17)=34.37, p=.0001), O1 (F(1,17)=112.97, p=.0001), O2 (F(1,17)=79.22, p=.0001), and Pz (F(1,17)=58.85, p=.0001). These were due to increases in alpha activity under eyes closed when compared to eyes open.

Beta Activity

Absolute Power

The ANOVA on beta power indicated there was a time main effect at O1 (F(7,119)=3.25, p=.0034) due to more beta activity at B1430 and B1830 than at the other testing times. There also was an increase in beta at D0230 when compared with D0630 (see table 4). There were eyes

main effects at C3 (F(1,17)=51.60, p=.0001), C4 (F(1,17)=58.17, p=.0001), Cz (F(1,17)=52.29, p=.0001), Fz (F(1,17)=43.78, p=.0001), O1 (F(1,17)=57.10, p=.0001), O2 (F(1,17)=57.20, p=.0001), and Pz (F(1,17)=59.78, p=.0001). These were due to increased beta activity under eyes closed in comparison to eyes open.

Table 3.
Mean alpha activity at each testing time.

Data Type	Electrode	B1030	B1430	B1830	D0230	D0630	D1030	D1430	D1830
Absolute	Fz	28.05	26.79	28.22	31.23	22.85	22.02	29.87	22.59
Power	C3	25.90	27.60	24.98	30.53	19.69	22.63	26.83	22.66
	C4	23.57	23.15	27.11	25.74	20.51	21.65	29.49	21.36
	Cz	32.82	34.40	36.36	40.04	27.09	29.48	40.21	29.10
	Pz	49.53	58.71	52.23	61.44	38.29	46.95	57.42	45.39
	O1	47.88	44.33	45.10	52.38	35.17	30.80	42.67	32.17
	O2	40.05	39.44	40.25	46.69	33.68	29.95	36.21	29.87
Log	Fz	2.85	2.87	2.85	2.84	2.68	2.58	2.93	2.74
Power	C3	2.86	2.89	2.81	2.85	2.65	2.64	2.86	2.71
	C4	2.76	2.72	2.85	2.74	2.71	2.59	2.94	2.73
	Cz	2.96	3.01	2.99	2.95	2.84	2.75	3.11	2.92
	Pz	3.34	3.44	3.33	3.31	3.10	3.06	3.41	3.24
	O1	3.13	3.11	3.13	3.06	2.79	2.69	3.12	2.86
	O2	3.09	3.13	3.14	2.97	2.80	2.70	3.05	2.90
Relative	Fz	1.38	1.40	1.37	1.39	1.24	1.15	1.36	1.20
Power	C3	1.53	1.51	1.51	1.56	1.39	1.34	1.45	1.37
	C4	1.46	1.44	1.53	1.50	1.39	1.30	1.49	1.34
	Cz	1.39	1.41	1.42	1.44	1.33	1.22	1.43	1.28
	Pz	1.64	1.66	1.67	1.68	1.55	1.48	1.65	1.55
	O1	1.75	1.71	1.78	1.75	1.64	1.52	1.75	1.63
	O2	1.70	1.74	1.78	1.72	1.63	1.54	1.76	1.64

Log Natural Transformed Power

There was a single time main effect at O1 (F(7,119)=3.33, p=.0029) which was due to more beta activity at B1430 and B1830 than at the other testing times. This was followed by a decrease in beta activity from D0230 to D0630 (see table 4). There were eyes main effects at C3 (F(1,17)=55.73, p=.0001), C4 (F(1,17)=74.35, p=.0001), Cz (F(1,17)=70.53, p=.0001), Fz (F(1,17)=52.84, p=.0001), O1 (F(1,17)=123.22, p=.0001), O2 (F(1,17)=116.82, p=.0001), and Pz (F(1,17)=102.75, p=.0001). These were due to increased beta activity under eyes closed in comparison to eyes open.

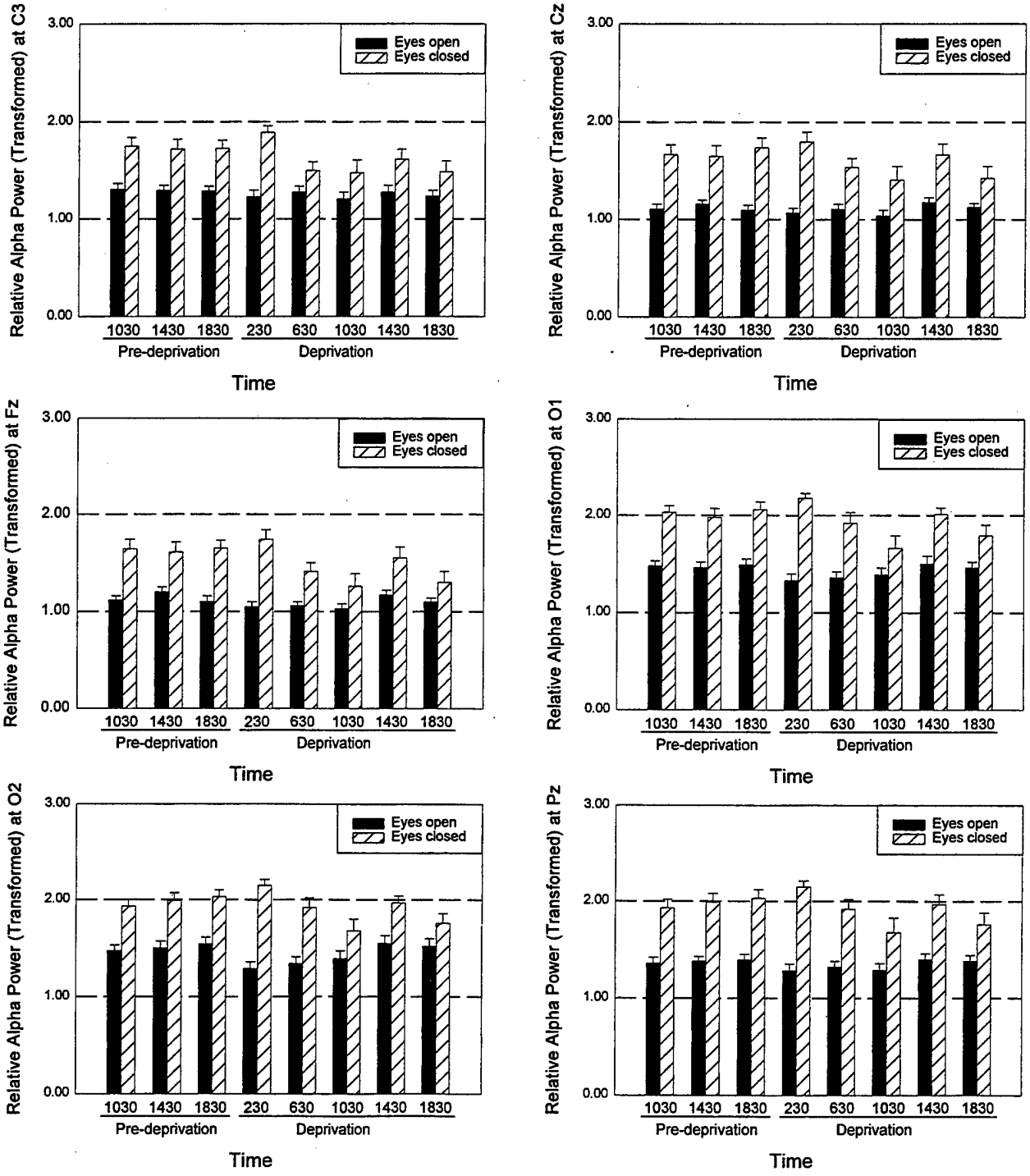

Figure 9. Effects of testing time and eye closure on relative alpha activity at several electrodes.

Transformed Relative Power

The ANOVA indicated time-by-eyes effects at O1 ($F(7,119)=3.79$, $p=.0009$) and O2 ($F(7,119)=2.45$, $p=.0222$). These effects were due to differences in the amount of beta activity recorded at eyes open across the different testing times for both electrodes. There was less beta recorded at D1830 than most of the remaining times, while there was an increase in beta at B1430 compared with D1030 (see figure 10). There was a time main effect at Pz ($F(7,119)=2.05$, $p=.0541$) due to more beta recorded at D0630 than B1430 or D0230. Less beta was detected at D1030 when compared to B1830 and D0630. Also, there was more beta recorded at D0630 than D1030 or D1430. There were eyes main effects at C3 ($F(1,17)=119.06$, $p=.0001$), C4 ($F(1,17)=136.14$, $p=.0001$), Cz ($F(1,17)=159.68$, $p=.0001$), Fz ($F(1,17)=86.60$, $p=.0001$), O1 ($F(1,17)=114.65$, $p=.0001$), O2 ($F(1,17)=65.07$, $p=.0001$), and Pz ($F(1,17)=255.99$, $p=.0001$). These effects were due to more beta activity recorded under eyes open than at eyes closed.

Tests For Normality

Normality was tested by examining skewness and kurtosis for each of the different transformations. Values of skewness and kurtosis which were greater than 1 were interpreted as indicating that the distributions had heavier tails than the normal distribution. Table 5 shows the skewness and kurtosis values for each of the electrodes tested. For absolute power, 41 out of 56 values of skewness failed the test for normality, while 39 failed for kurtosis. The log natural transformation indicated 2 failed values for skewness and 4 for kurtosis. Relative power showed 10 values failing normality for skewness and 12 for kurtosis.

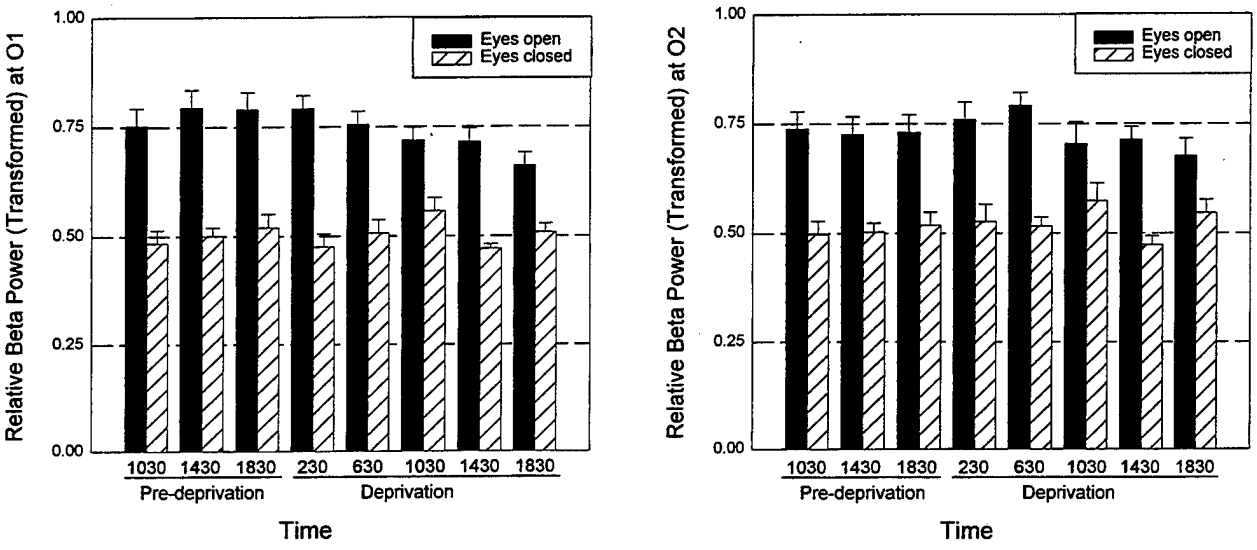

Figure 10. Effects of testing time and eye closure on transformed relative beta power at O1 and O2.

Table 4.
Mean beta activity at each testing time.

Data Type	Electrode	B1030	B1430	B1830	D0230	D0630	D1030	D1430	D1830
Absolute	Pz	4.64	5.02	4.70	4.65	4.83	3.97	4.80	5.08
Power	O1	3.82	4.45	4.36	3.83	3.41	3.43	3.62	3.40
Log	Pz	1.64	1.67	1.64	1.59	1.64	1.49	1.65	1.66
Power	O1	1.45	1.55	1.55	1.46	1.35	1.37	1.41	1.33
Relative	Pz	0.58	0.57	0.59	0.57	0.62	0.54	0.56	0.57
Power	O1	0.62	0.65	0.65	0.63	0.63	0.64	0.59	0.58

Discussion

As was expected based on the findings of Gasser, Bächer, and Möchs (1982), the log natural and arcsine transformations clearly improved the normality of the data. As a result, there were differences in the number and location of statistically significant effects. Of 36 significant time effects, 10 were found on the absolute power data, 12 were found on transformed absolute power, and 14 were found on transformed relative power. Of the instances in which significance was obtained on either of the absolute power measures, there was agreement across both only 40 percent of the time. Agreement across all three measures occurred only 16 percent of the time. Thus, data transformations will have some impact on conclusions regarding the presence or absence of effects in a given data set. In addition, the choice of a specific data representation (relative versus absolute power), regardless of whether or not it is transformed, may affect the interpretation of the significant findings.

Whereas interpretations of absolute power versus transformed absolute power were quite similar, the same cannot be said for relative power. A review of the results based on absolute power showed that when there were significant effects on transformed and untransformed absolute power, the form of the relationship was consistent. Where there were interactions between the time and eyes factors, analysis of simple effects indicated the time effect occurred because of differences in the eyes closed data regardless of whether or not the data were transformed. Also, when contrasts were performed to pinpoint the precise nature of the effect, the conclusions drawn from these contrasts were consistent despite the data transformations. For instance, in the case of theta activity, it was often found that theta was lower at 0230 on the deprivation day than it was at many of the other times (under eyes closed). This was true regardless of whether the data were analyzed as absolute power or log-natural-transformed absolute power (although different electrodes were affected differently). Furthermore, when differences in activity between eyes open and eyes closed were found, visual inspection of the results always revealed greater power under eyes closed relative to eyes open. Thus, regardless

Table 5.
Skewness and kurtosis values for the data recorded from each electrode.

Location		Absolute Power		Log Natural Power		Relative Power	
	band	Skewness	Kurtosis	Skewness	Kurtosis	Skewness	Kurtosis
Open	Fz delta	2.33	8.86	0.43	0.63	0.13	-0.38
	theta	1.76	4.11	0.35	0.06	-0.28	0.31
	alpha	1.24	1.59	0.09	-0.47	-0.14	0.11
	beta	0.74	-0.11	0.13	-0.92	-0.01	-0.98
	C3 delta	0.75	0.84	-0.10	-0.66	0.15	0.21
	theta	1.05	1.12	0.16	-0.43	-0.02	0.30
	alpha	2.27	9.86	0.06	-0.15	-0.01	-0.20
	beta	0.91	0.81	0.08	-0.12	-0.11	-0.10
	Cz delta	0.75	0.49	-0.11	-0.40	0.23	-0.07
	theta	1.29	2.01	0.34	-0.13	0.03	-0.12
	alpha	1.54	4.28	0.00	-0.37	-0.18	0.50
	beta	0.84	0.33	0.14	-0.65	-0.01	-0.67
	C4 delta	1.37	2.87	0.16	0.02	0.44	-0.17
	theta	1.76	5.28	0.43	-0.03	0.06	-0.30
	alpha	0.90	0.31	-0.18	-0.50	-0.37	0.11
	beta	1.23	2.12	0.30	-0.29	0.11	-0.43
	Pz delta	1.29	2.12	0.18	-0.06	0.25	0.03
	theta	2.32	8.65	0.57	0.95	0.24	0.18
	alpha	1.70	4.94	-0.03	-0.40	-0.36	-0.45
	beta	0.88	0.99	0.08	-0.09	-0.09	-0.23
	O1 delta	2.02	6.30	0.30	0.86	0.04	-0.57
	theta	1.98	4.86	0.59	0.48	0.35	0.07
	alpha	3.92	23.57	0.39	0.20	-0.10	-0.56
	beta	0.68	0.26	0.00	-0.75	-0.15	-0.88
	O2 delta	3.47	16.74	0.95	1.70	0.46	-0.13
	theta	2.02	5.15	0.52	0.17	0.44	0.02
	alpha	2.17	6.24	0.07	-0.48	-0.27	-0.91
	beta	1.29	2.16	0.23	0.21	0.05	0.20
Closed	Fz delta	4.61	28.79	1.04	1.65	1.04	1.03
	theta	2.64	8.66	0.58	-0.35	0.61	-0.32
	alpha	1.16	1.52	-0.59	-0.22	-0.73	0.16
	beta	0.91	0.69	-0.19	-0.27	-0.54	0.02
	C3 delta	3.46	16.89	0.92	1.08	1.02	1.47
	theta	2.61	9.60	0.46	-0.24	0.92	0.42
	alpha	1.15	1.16	-0.62	0.19	-0.91	0.92
	beta	0.83	0.87	-0.38	0.06	-0.68	0.30
	Cz delta	6.61	57.33	1.10	2.42	1.19	2.31
	theta	2.08	4.28	0.55	-0.36	0.71	-0.13
	alpha	1.01	0.55	-0.51	-0.28	-0.72	0.09
	beta	0.83	0.67	-0.41	0.15	-0.73	0.48
	C4 delta	4.94	38.59	0.54	0.63	1.14	2.98
	theta	2.68	9.17	0.49	-0.22	0.88	0.13
	alpha	0.90	0.41	-0.72	0.16	-0.90	0.41
	beta	0.77	0.71	-0.42	0.11	-0.73	0.50
	Pz delta	2.00	6.65	0.32	-0.28	1.11	2.01
	theta	2.56	7.12	0.54	-0.01	1.10	0.70
	alpha	1.01	0.57	-0.95	0.96	-1.70	3.31
	beta	1.07	1.97	-0.31	0.15	-0.59	0.30
	O1 delta	3.43	20.08	0.36	0.18	1.10	1.70
	theta	2.36	6.47	0.19	-0.15	1.49	2.12
	alpha	1.37	2.21	-0.94	0.50	-1.84	3.75
	beta	0.79	0.67	-0.44	-0.02	-0.76	0.30
	O2 delta	2.36	9.40	0.20	-0.20	1.33	2.59
	theta	3.28	12.9	0.35	0.42	1.36	1.51
	alpha	1.25	1.63	-0.98	0.59	-1.74	2.82
	beta	0.85	0.79	-0.39	0.03	-0.63	0.16

of whether absolute power or transformed absolute power was analyzed, the findings were quite similar to one another.

Transforming the data into relative power, however, leads to different interpretations of the results. This was particularly noticeable in every band with the exception of alpha activity. For instance, although the significant interactions in relative theta were found to be a result of differences among testing times at eyes closed (a finding similar to the one observed with absolute power), the overall trend was for more relative theta power to have occurred under eyes open than eyes closed (the opposite of what was observed with absolute power). The apparent inconsistency was attributable to the fact that alpha was substantially increased when subjects closed their eyes and, since the other types of activity (delta, theta, and beta) changed little in comparison, the *relative power* in each of the other bands appeared *greater* (rather than less) under eyes open than eyes closed. Thus, in the absence of information about the other EEG bands, one might have assumed that the actual magnitude of theta decreased as a function of eye closure when, in fact, the opposite was true. Because of this, caution should be exercised when attempting to interpret relative power because changes in the various bands are not mutually exclusive (since relative power reflects the amount of activity in each band in comparison to the amount of activity in all others).

This caution aside, it seems that relative power analyses may be slightly more sensitive to treatment effects than either type of absolute power analysis. In the present study, 14 of the 36 time main effects were found on relative power as opposed to 12 on transformed absolute power, and 10 on untransformed absolute power. The totals for time-by-eyes interactions for each type of data were 15, 9, and 11, respectively. This improved sensitivity probably results from slight decreases in the error variance in the relative measures since they tend to show less severe fluctuations from one condition to the next or from one subject to the next. However, as was stated above, this slight improvement in sensitivity comes with the associated cost of more difficult interpretations of the data.

In conclusion, the present findings suggest that, while ANOVA is rather robust with regard to violations of the normality assumption, it is not robust to the extent that the data distributions will not exert some impact on the overall results. However, the practical impact appears to be rather small when comparing the changes in normality to the observed changes in the number of statistically significant findings. There certainly is not a one-to-one improvement between the quality of the outcome measures and the degree to which the data are normally distributed. This was evident from the fact that transforming absolute power into its log natural reduced problems with skewness 69 percent (from 73 percent to 4 percent), but increased the number of statistically significant effects only 6 percent (from 27 percent to 33 percent). A similar relationship was observed in the relative power data (i.e., the transformation improved normality but did not substantially change sensitivity). Thus, the small changes as a function of data transformations may not be worth the required computational overhead, at least in a repeated-measures design.

References

Bender, R., Schultz, B., Schultz, A., and Pichlmayr, I. 1992. Testing the gaussianity of the human EEG during anesthesia. Methods of Information in Medicine. 31: 56-59.

Gasser, T., Bächer, P., and Möcks, J. 1982. Transformations towards the normal distribution of broad band spectral parameters of the EEG. Electroencephalography and Clinical Neurophysiology. 53: 119-124.

Hayes, W. L. 1973. Statistics for the social sciences. New York: Holt, Rinehart and Winston, Inc.

Kirk, R. E. 1968. Experimental design: Procedures for the behavioral sciences. Belmont: Brooks/Cole Publishing Company.