

Dietary Boron, Brain Function, and Cognitive Performance

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Although the trace element boron has yet to be recognized as an essential nutrient for humans, recent data from animal and human studies suggest that boron may be important for mineral metabolism and membrane function. To investigate further the functional role of boron, brain electrophysiology and cognitive performance were assessed in response to dietary manipulation of boron (≈ 0.25 versus ≈ 3.25 mg boron/2000 kcal/day) in three studies with healthy older men and women. Within-subject designs were used to assess functional responses in all studies. Spectral analysis of electroencephalographic data showed effects of dietary boron in two of the three studies. When the low boron intake was compared to the high intake, there was a significant ($p < 0.05$) increase in the proportion of low-frequency activity, and a decrease in the proportion of higher-frequency activity, an effect often observed in response to general malnutrition and heavy metal toxicity. Performance (e.g., response time) on various cognitive and psychomotor tasks also showed an effect of dietary boron. When contrasted with the high boron intake, low dietary boron resulted in significantly poorer performance ($p < 0.05$) on tasks emphasizing manual dexterity (studies II and III); eye-hand coordination (study II); attention (all studies); perception (study III); encoding and short-term memory (all studies); and long-term memory (study I). Collectively, the data from these three studies indicate that boron may play a role in human brain function and cognitive performance, and provide additional evidence that boron is an essential nutrient for humans. — *Environ Health Perspect* 102(Suppl 7): 65–72 (1994)

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Introduction

Although the trace element boron has yet to be recognized as an essential nutrient for humans, data from several animal and human studies suggest that boron may play a role in cell membrane function, mineral and hormone metabolism, and enzyme reactions (1). Among humans, average daily intake of dietary boron ranges between 1.7 and 7 mg (2), with fruits, nuts and vegetables being the major food sources (3). Measures of brain electrophysiology and behavior have been shown to be

sensitive to nutritional inadequacy in both animals and humans (4–10), and frequently have been used in the fields of toxicology and pharmacology to assess functional sequelae (11–13). To investigate further the functional role of boron for humans, the electroencephalogram (EEG) and performance on a battery of cognitive and psychomotor tasks were assessed in response to dietary manipulation of boron in three independent studies with healthy older adults (14,15). An overview of these studies and a summary of their findings are presented in this report.

Methods

Subjects

Study I. Thirteen Caucasian postmenopausal women aged 50 to 78 years were recruited through regional and national advertising to participate in a six-month, live-in study of magnesium and boron nutrition. All subjects were in good health as determined by an extensive health history, biochemical analyses of blood and urine samples, chest x-ray, electrocardiogram (EKG), clinical examination, and psychological interview and testing. Subjects were not on estrogen replacement therapy and showed no signs of osteoporosis as determined by dual-photon absorptiometry. All but one subject were right-handed.

Studies II and III. Fifteen healthy older adults, five men, five postmenopausal

women on estrogen replacement therapy, and five postmenopausal women not on estrogen replacement therapy, were recruited from the local community to participate in each study. Health status was determined by blood and urine analyses, an extensive medical and psychological history, and clinical assessment of blood pressure and weight. All subjects were Caucasian, right-handed (except one subject in study III); subjects ranged in age from 44 to 69 years in study II, and from 49 to 61 years in study III. In study II, one woman not receiving estrogen began to menstruate shortly after the study began and her data were excluded. In study III, one man withdrew during the first month.

All Studies. Following written and verbal explanation, each individual gave his or her written consent to participate. Studies were approved by the Institutional Review Board of the University of North Dakota and the Human Studies Review Committee of the U.S. Department of Agriculture, and were conducted in accordance with the principles of the Helsinki Doctrine of 1975 as revised in 1983.

Diet

All Studies. Subjects in all three studies were fed a diet consisting of conventional foods on a three-day menu rotation (16). The diet included chicken, beef, pork, potatoes, rice, bread, and milk, but was low in vegetables and fruits. The basal diet supplied approximately 115 mg magnesium

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and 0.23 mg boron/2000 kcal/day, and was supplemented as necessary to approximate typical intakes and ensure nutritional adequacy of all vitamins and minerals except magnesium and boron (16). With supplementation, dietary copper intake was still marginal (1.6 mg/2000 kcal) in studies I and II. To remove this potential source of confounding from study III, the basal diet was supplemented with an additional 0.8 mg Cu/day, as copper sulfate (17). Energy in the diet was distributed as 11% protein, 54% carbohydrate, and 35% fat; caloric intakes necessary to maintain initial body weight ($\pm 2\%$) were determined separately for each subject. Water was consumed *ad libitum* from the Grand Forks, ND water supply, which has a boron concentration of approximately 15 ng/ml, by analysis. If a typical consumption of three 500 ml glasses of water per day is assumed, this source added only 0.022 mg to the daily intake of boron.

Study I. Following a 21-day equilibration period during which the diet was supplemented with 200 mg magnesium and 3 mg boron/2000 kcal/day, as magnesium gluconate and sodium borate capsules, respectively, each subject was given all four supplement combinations created by the factorial crossing of 0 (placebo) and 200 mg magnesium with 0 (placebo) and 3 mg boron for 42 days each. Magnesium and boron placebo capsules both contained lactose powder. Supplements were administered in a double-blind, Latin squares order.

Studies II and III. These studies began with a 14-day equilibration period, followed by a 63-day boron-depletion period, and concluded with a 49-day boron-repletion period. The basal diet was supplemented with 3 mg boron/day, as sodium borate, during the equilibration and boron repletion periods. During all dietary periods in study III, the diet also was supplemented with 200 mg magnesium/day, as magnesium gluconate.

Procedure

Study I. Subjects resided 24 hr/day on the metabolic research unit at the Grand Forks Human Nutrition Research Center, which permitted strict control of dietary intakes, exercise, and data collection, and provided a common environment. Subjects were chaperoned on all outings to ensure compliance with study protocol. All urine and feces were collected, and blood samples were obtained by venipuncture on a weekly basis. To familiarize subjects with electroencephalogram (EEG) and performance-test-

ing procedures, two sessions of each type were conducted during the equilibration period; these data were not analyzed. During subsequent periods of magnesium and boron supplementation, data were collected twice (once in the morning and once in the afternoon) during the last week of each 42-day period.

Studies II and III. Subjects lived at home and maintained their usual work and recreational activities. One meal per day (either breakfast or lunch) was consumed in the laboratory Monday through Friday. Foods for all other meals were packed in coolers for consumption at home; foods for weekend meals were taken home on Fridays. All meals were prepared, packaged, and served in disposable paper or plastic containers to prevent contamination. Twenty-four-hr urine samples were collected three times per week, and a blood sample was obtained by venipuncture once each week. Subjects were led to believe that their compliance with the dietary regimen was monitored throughout the study by ongoing review of biochemical analyses of blood and urine samples. EEG and performance data were collected once during the equilibration period to familiarize subjects with the procedures, but were not analyzed. During subsequent boron depletion and repletion periods, data were collected approximately every third week, or three times during each dietary period, at the same time of day throughout the study.

Electrophysiology Recording and Processing

Prior to recording the EEG, the subject was fitted with a stretchable cap containing tin alloy electrodes located over the left and right frontal (F_3 and F_4 in the notation of the International Ten-Twenty System of Electrode Placement), temporal (T_3 and T_4), parietal (P_3 and P_4), and occipital (O_1 and O_2) lobes. Each recording electrode was referenced to linked-ear electrodes balanced for impedance, with a vertex ground. Impedances were typically less than 5 kohm and always less than 10 kohm. During EEG collection, the subject was seated in a comfortable chair in a darkened, sound-proofed room. EEG records were made while the subject was at rest (i.e., the subject was instructed to relax, and there were no explicit task demands) for 40 sec with the eyes open, and then for 40 sec with the eyes closed. To obtain more reliable measures of brain activity during rest, the EEG was recorded during three 40-sec eyes-open periods counterbalanced with three 40-sec eyes-closed periods.

EEG data were amplified by low-noise, battery-powered instrumentation amplifiers with an approximate gain of 70,000, band-pass filtered with a 3-dB roll-off at approximately 0.15 and 34 Hz, digitized, and recorded on a computer for further processing off-line. The difference in potentials between the recording electrode over each lobe and the reference electrodes was sampled 512 times/sec and 4-point smoothed to yield an effective sampling frequency of 128 and a Nyquist frequency of 64 Hz. To remove extracerebral artifact, signals were displayed off-line in 1-sec epochs and visually edited by a trained technician; only epochs free of artifact were retained for statistical analysis.

Following editing, EEG data recorded from each electrode location (i.e., lobe) were spectrally analyzed by the Cooley-Tukey Fast Fourier transform. This technique converts time series data to a representation in the frequency domain, and yields a standardized measure of amplitude or signal power. Power, determined for each electrode location, corresponds to the absolute amount of activity in each frequency component of the complex EEG signal, and reflects the degree of synchronous cortical activity among neurons in a localized region of the brain. Given 1-sec epochs, the power spectrum had a resolution of 1 Hz. Further computation allowed the mean power of the signal to be determined for each of four frequency bands: 1 to 3 Hz (δ), 4 to 7 Hz (θ), 8 to 12 Hz (α), and 13 to 18 Hz (β). Coherence, the correlation between a pair of signals for each frequency band, was computed for all possible pairs of electrode recording sites to assess the relationship between activity in different regions of the brain. Coherence reflects symmetry in activity of populations of cortical neurons, and thus the degree of coordination and integration among brain regions.

Cognitive and Psychomotor Assessment

Table 1 lists the cognitive and psychomotor tasks performed by subjects in each study, and the area of function emphasized by each task. These tasks were selected from a larger battery contained in the Cognition Psychomotor Assessment System (CPAS), a software package developed by the author and successfully used in previous behavioral studies of other nutrients (18). The tasks in this battery are computerized versions of standardized tasks commonly used in neuropsychologic assessment and experimental cognitive psy-

Table 1. Cognition psychomotor assessment system subset of tasks used in boron studies.

Study	Task name	Function
I II ^a III ^a	Tapping	Psychomotor
I II ^a III	Pursuit	Psychomotor
I	Trails	Psychomotor
I ^a II ^a III ^a	Search-count	Attention
I	Continuous vigilance	Attention
I II III ^a	Color-name identification	Perception
I II III	Time estimation	Perception
I ^a II ^a III ^a	Symbol-digit	Memory
I	Letter recognition	Memory
I	Shape recognition	Memory
I	Cube recognition	Memory
I ^a	Word recognition	Memory
I	Maze	Spatial

^a Study showing significant ($p < 0.05$) effect of dietary boron on performance.

chology. All tasks were administered on an Apple IIe microcomputer located in a specially-built cubicle within a larger room; tasks were performed with instruction and supervision provided by a trained technician. Test sessions required 60 (studies II and III) or 90 (study I) min to complete. Throughout testing, subjects wore headphones to block extraneous noise.

In the Tapping task, two- and four-key sequences were tapped on a computer keyboard as rapidly as possible for 30 sec; the number of complete sequences tapped was the performance measure. In the Pursuit task, a joystick-controlled cursor was used to track (i.e., follow) a computer-controlled cursor moving across the computer screen in a random or nonrandom (i.e., predictable) path; trials lasted 30 sec and percent-time-on-target (i.e., cursors within 2 mm of each other) was the performance measure. In the Search-Count task, a computer screen filled with letters of the alphabet was searched for the presence (search only) or number (search and count) of one or more target letters; accuracy and response time to press the appropriate key on the computer keyboard were the performance measures. In the Color-name Identification task, the name of a color (e.g., red) was presented on the computer screen in a consistent (i.e., red), neutral (e.g., white) or inconsistent (e.g., blue) color. The subject was instructed to identify either the name of the color or the color in which the name was presented, and in both cases to ignore the irrelevant stimulus dimension. Keys on the keyboard were covered with colored tape and subjects responded by pressing the key covered by the appropriate color; accuracy and time to respond were the performance measures. In the Time Estimation task, subjects estimated time intervals of 15, 30, and 60 sec, twice each in counterbalanced order; direc-

tion and amount of error in estimates were the performance measures. In the Symbol-Digit task, symbols (e.g., τ \downarrow $=$ \vdash \neg \perp \ulcorner \lrcorner) were paired with the digits 0 to 9 at the top of the computer screen; and when one of the symbols was presented at the bottom of the screen, the corresponding digit was pressed on the computer keyboard; accuracy and response-time were the performance measures. In the Word Recognition task, 20 common words (e.g., chair) were presented for study one at a time for 1 sec each. This was followed 1 min later by a test phase using 40 words—the original 20 words randomly intermixed with 20 new words conceptually related to the original ones (e.g., table). Accuracy and time to respond “same” or “different” using the S and D keys on the keyboard were the performance measures.

As indicated in Table 1, several other tasks were administered during study I, but did not show significant ($p < 0.05$) effects of dietary boron. To conserve space, those tasks will not be described here. However, collectively those tasks assessed function in the same areas as those described above.

Data Analysis

Electroencephalogram. Mean EEG power data from each of the four frequency bands recorded from each electrode location were \log_{10} transformed to achieve a more symmetric distribution prior to statistical analysis. Percent-total power, a measure of the relative distribution of power among the different frequency bands for each electrode location, was determined by calculating the percentage of total power across the frequency spectrum represented in each frequency band. This ratio of absolute power for each band to the sum of power present in all frequency bands (1–18 Hz) was arcsin-transformed to normalize the measure prior to statistical analysis. As a

measure of the frequency distribution of cortical activity, percent-total power defines the dominant frequency in the signal and is highly sensitive to frequency shifts. To assess the degree of asymmetry between the two hemispheres, reflecting the spatial distribution of cortical activity, the difference between mean, untransformed left- and right- hemisphere power measures was determined for each frequency band recorded from the frontal, temporal, parietal, and occipital lobes. This left-minus-right-contrast was then standardized (divided) by the sum of the component power measures. To assess cortical responsiveness to external stimulation, alpha reactivity was computed by subtracting alpha power determined during eyes-open periods from alpha power determined during eyes-closed periods. Finally, raw coherence values from each of the four frequency bands were transformed by Fisher's z to achieve a more normal distribution. Each of the above EEG measures was averaged across the three rest periods during each recording session, and then across sessions within each dietary period, separately for eyes-closed and eyes-open conditions. Thus, these data reflect the typical level of brain electrical activity during each of the two resting conditions during each dietary period.

Cognitive and Psychomotor Performance.

Mean number of sequences tapped across all trials and counted separately for two- and four-key sequence trials were calculated for Tapping. Mean percent time-on-target across all trials, and counted separately for nonrandom and random trials, were calculated for Pursuit. Mean relative and absolute errors in estimate across all trials, and counted separately for 15-, 30-, and 60-sec trials were calculated for Time Estimation. Median accuracy and response times across all search-only trials, across all search-and-count trials, and counted separately for search-and-count trials with targets present and targets absent were calculated for Search-Count. Median accuracy and response times across all name identification trials, and counted separately for consistent, neutral, and inconsistent presentation color trials were calculated for the name-identification part of Color-name. These same measures were also calculated for the color identification part of the task. In addition, the facilitatory and inhibitory effect on response time of the irrelevant stimulus dimension was determined by subtracting the median response time for neutral trials from that for consistent trials and inconsistent trials, respectively.

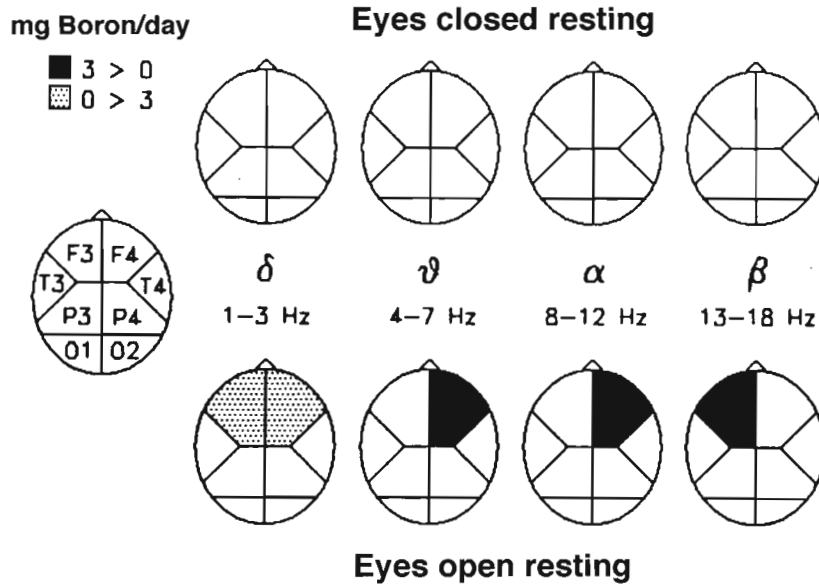


Figure 1. Boron effects on percent-total electroencephalogram (EEG) power (study I). Significant ($p < 0.05$) dietary boron effects on mean percent-total EEG power during eyes-closed and eyes-open conditions, separately for each recording site and frequency band. Diet with greater proportion is keyed. Labeled head at far left identifies each recording site relative to the region of the brain sampled.

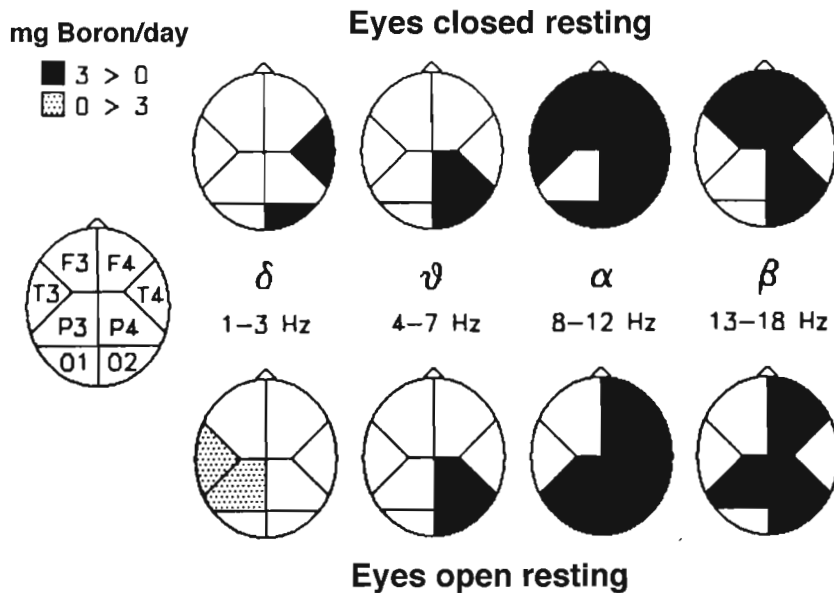


Figure 2. Boron effects on electroencephalogram (EEG) power (study II). Significant ($p < 0.05$) dietary boron effects on mean EEG power during eyes-closed and eyes-open conditions, separately for each recording site and frequency band. Diet with greater power is keyed. Labeled head at far left identifies each recording site relative to the region of the brain sampled.

Median accuracy and response times across all test trials were calculated for Word Recognition. Each of the above performance measures was averaged across test

sessions within each dietary period; thus they represent more stable measures of performance than would data from any single session.

All Functional Measures. For study I, dietary effects on EEG and performance measures were tested for significance by a $B \times \text{Mg} \times \text{Period}$ repeated-measures analysis of variance; Period was included as a factor in the model to remove effects associated with order of supplement administration (i.e., time effects). For studies II and III, dietary effects on all measures were tested for significance by contrasting the boron depletion and boron repletion conditions by the Student's t statistic for repeated-measures designs. To maximize statistical power by increasing sample size, data from the three subgroups of subjects in studies II and III (men, women on estrogen therapy, and women not on estrogen therapy) were combined for all analyses. This approach was deemed appropriate because preliminary analysis revealed no group differences in the direction of changes related to the dietary manipulation and *post hoc* examination of significant effects confirmed that group membership was not systematically related to study findings. All data manipulation and statistical contrasts were performed with release 5.18 of Statistical Analysis System software (SAS) (19). In the presentation of results to follow, effects are described as significant when $p < 0.05$.

Results

Electroencephalogram

Studies I and II were similar in showing numerous effects of dietary boron on the EEG recorded while subjects were at rest. However, study III found no significant effects of boron intake on this physiologic measure of brain function.

Study I. Although there were numerous effects of dietary magnesium on the EEG, the number of boron \times magnesium interactions did not exceed chance nor did they involve the following main effects of dietary boron. When contrasted with the high boron intake, low dietary boron significantly increased delta (1–3 Hz) power in left parietal and left occipital regions under the eyes-open condition. These were the only significant effects of diet on absolute power. However, as shown in Figure 1, low boron increased percent-total delta power in the frontal regions, while decreasing percent-total right frontal theta (4–7 Hz), percent-total right frontal alpha (8–12 Hz), and percent-total left frontal beta (13–18 Hz) power. These effects were again limited to the eyes-open condition. Under both recording conditions, low boron generally increased signal coherence,

particularly in the delta frequencies among posterior regions of the brain.

Study II showed the greatest number of effects of dietary boron on the EEG parameters. Figure 2 presents significant findings from analysis of absolute power. When contrasted with the high boron intake, low dietary boron increased delta power in the left temporal and parietal regions (see study I), decreased alpha power across the head, decreased right frontal beta power, and decreased theta and beta power in the right parietal and right occipital regions. With the exception of the first finding, all effects were significant under both eyes-closed and eyes-open recording conditions. Figure 3 presents significant findings from analysis of percent-total power. Low boron increased percent-total delta power in the posterior regions (see study I), decreased percent-total alpha power across the head, and decreased percent-total theta and beta power in the parietal regions. Low boron also resulted in increased bias toward greater activity in the left than right hemisphere in the parietal region under the eyes-closed condition, and in the frontal and parietal regions under the eyes-open condition. In addition, low boron significantly decreased alpha reactivity in the right frontal and left occipital regions. Finally, as shown in Figure 4, low boron increased coherence among several regions across the head in the delta frequencies, and decreased coherence in the theta, alpha, and beta frequencies among posterior regions, under both eyes-open and eyes-closed recording conditions.

Cognitive and Psychomotor Performance

As shown in Table 1, all three studies were consistent in showing an effect of dietary boron on performance of two tasks, Search-Count and Symbol-Digit. Performance on three other tasks, Tapping, Pursuit, and Color-name Identification, was affected by dietary boron in one or two, but not all three of the studies. There were no significant effects of boron intake on the performance of seven other tasks; however, six of these tasks were administered in only one study (study I). One additional task, Word Recognition, showed an effect of boron intake, but was administered only during one study (study I). Accuracy (i.e., error rate) was not significantly affected by boron intake in any of the three studies. Further, these performance measures showed no significant effects associated with magnesium intake or

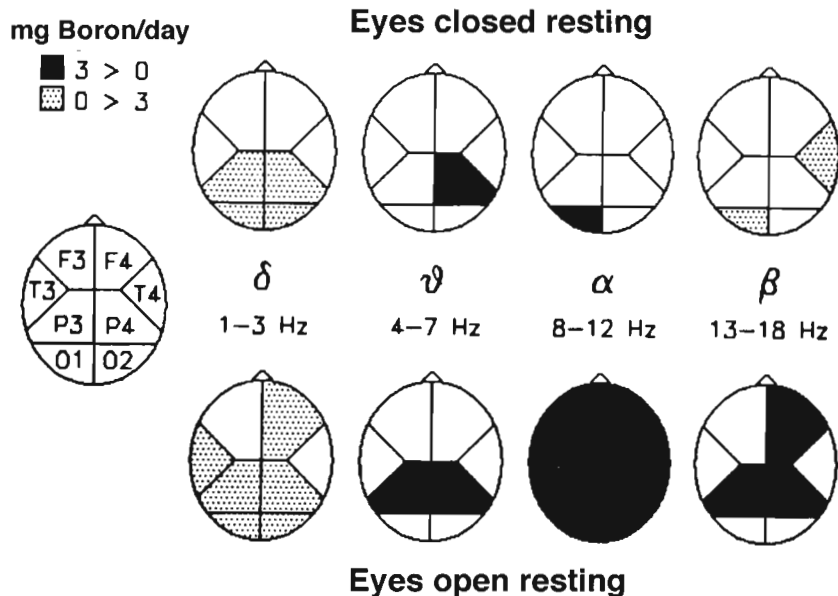


Figure 3. Boron effects on percent-total electroencephalogram (EEG) power (study II). Significant ($p < 0.05$) dietary boron effects on mean percent-total EEG power during eyes-closed and eyes-open conditions, separately for each recording site and frequency band. Diet with greater proportion is keyed. Labeled head at far left identifies each recording site relative to the region of the brain sampled.

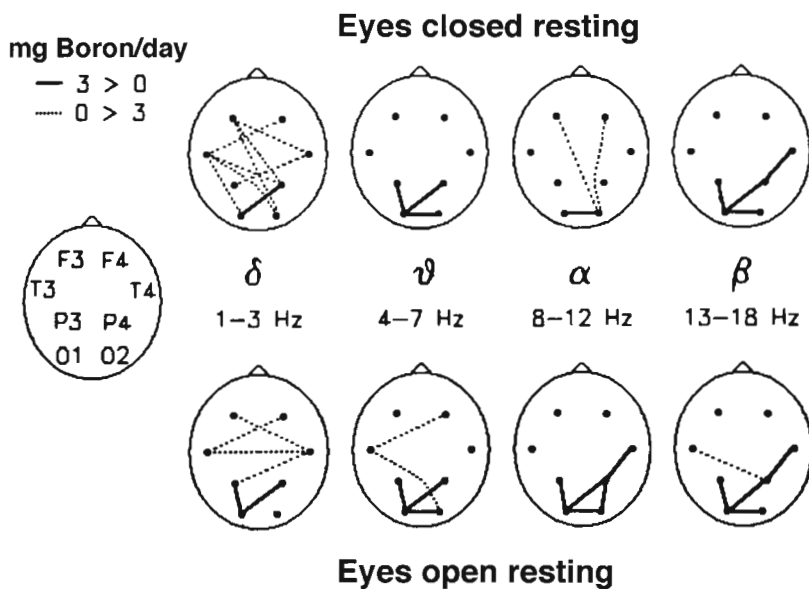


Figure 4. Boron effects on electroencephalogram (EEG) coherence (study II). Significant ($p < 0.05$) dietary boron effects on mean EEG coherence during eyes-closed and eyes-open conditions, separately for each recording site and frequency band. Diet with greater coherence is keyed. Labeled head at far left identifies each recording site relative to the region of the brain sampled.

the boron \times magnesium interaction in study I.

Psychomotor. Table 2 shows the effects of boron intake on the Tapping and

Pursuit tasks performed in all three studies. When contrasted with the high boron intake, low dietary boron resulted in fewer complete sequences tapped overall, and

Table 2. Effects of boron intake on tapping and pursuit performance.

Boron supplement, mg/day	Study I ^a		Study II		Study III	
	0	3	0	3	0	3
Tapping, No. tapped/30 sec						
All sequences	23.0 ± 0.3 ^b	23.0 ± 0.3	22.1 ± 1.0 ^d	24.2 ± 1.0	23.2 ± 1.0 ^c	24.6 ± 0.8
2-Key sequences	31.0 ± 0.4	31.1 ± 0.4	30.2 ± 1.3 ^d	32.5 ± 1.2	32.3 ± 1.2 ^c	33.6 ± 1.1
4-Key sequences	15.0 ± 0.2	14.8 ± 0.2	14.0 ± 0.7 ^d	15.9 ± 0.7	14.1 ± 0.8 ^d	15.5 ± 0.6
Pursuit, % time on target						
All paths	19.2 ± 0.6	18.5 ± 0.6	22.8 ± 2.5 ^d	26.4 ± 2.3	16.0 ± 1.7	17.5 ± 1.6
Random paths	16.3 ± 0.6	15.7 ± 0.6	23.4 ± 1.7	25.2 ± 1.5	15.7 ± 1.4	15.1 ± 1.0
Nonrandom paths	20.0 ± 0.7	19.2 ± 0.7	22.6 ± 2.9 ^d	26.6 ± 2.7	16.1 ± 1.9	18.1 ± 1.8

Table 3. Effects of boron intake on search-count response times (s).

Boron supplement, mg/day	Study I ^a		Study II		Study III	
	0	3	0	3	0	3
Search only	3.34 ± 0.08 ^b	3.15 ± 0.07	3.43 ± 0.32 ^d	2.63 ± 0.21	3.52 ± 0.33 ^d	3.02 ± 0.29
Search and count						
All conditions	7.37 ± 0.21	6.80 ± 0.20	7.05 ± 0.57 ^d	6.27 ± 0.52	7.73 ± 0.83 ^d	6.84 ± 0.66
Targets present	7.20 ± 0.20 ^c	6.62 ± 0.20	6.95 ± 0.57 ^d	6.18 ± 0.52	7.53 ± 0.79 ^d	6.72 ± 0.64
Targets absent	8.22 ± 0.27 ^c	7.32 ± 0.27	8.11 ± 0.83 ^c	6.83 ± 0.59	8.66 ± 1.02	8.15 ± 0.98

^a Boron main effects from B × Mg × Period ANOVA. ^b Mean ± standard error of the mean. ^c p < 0.05. ^d p < 0.01.

Table 4. Effects of boron intake on Color-name Identification response time(s).

Boron supplement, mg/day	Study I ^a		Study II		Study III	
	0	3	0	3	0	3
Name + color	844 ± 10.9 ^b	858 ± 10.8	774 ± 24.1	760 ± 21.3	783 ± 31.2 ^c	746 ± 32.4
Presentation color (name identification only)						
Consistent	772 ± 18.2	806 ± 18.1	729 ± 27.2	713 ± 24.5	731 ± 25.7 ^d	680 ± 27.5
Neutral	815 ± 15.2	833 ± 15.1	752 ± 32.1	738 ± 23.5	765 ± 31.6 ^d	718 ± 29.8
Inconsistent	907 ± 18.3	921 ± 18.2	813 ± 34.9	787 ± 26.7	822 ± 38.7	783 ± 41.5
Inhibition	92	88	61	49	57	65
Facilitation	43	27	23	25	34	38

^a Boron main effects from B × Mg × Period ANOVA. ^b Mean ± standard error of the mean. ^c p < 0.05. ^d p < 0.01.

Table 5. Effects of boron intake on symbol-digit and word recognition performance.

Boron supplement, mg/day	Study I ^a		Study II		Study III	
	0	3	0	3	0	3
Symbol-digit						
Response time(s)	2.30 ± 0.02 ^{b,c}	2.23 ± 0.02	2.14 ± 0.06 ^d	1.88 ± 0.05	2.27 ± 0.11 ^d	1.98 ± 0.08
Error, %	2.34 ± 0.43	2.65 ± 0.43	3.25 ± 0.36	2.85 ± 0.41	2.78 ± 0.55	2.26 ± 0.50
Word recognition						
Response time(s)	2.46 ± 0.04 ^c	2.33 ± 0.04	Not administered		Not administered	
Error, %	7.85 ± 0.73	7.44 ± 0.72	Not administered		Not administered	

^a Boron main effects from B × Mg × Period ANOVA. ^b Mean ± standard error of the mean. ^c p < 0.05. ^d p < 0.01.

fewer taps for both long and short sequences in studies II and III. Study II also found that low boron resulted in decreased percent time-on-target when all pursuit trials were combined, but particularly when the target was following a non-random (i.e., predictable) path. There were no significant dietary boron effects on psychomotor performance in study I.

Attention. Table 3 shows the effects of boron intake on Search-Count response times. When contrasted with the high boron intake, low dietary boron resulted in increased response times during search-and-count in all three studies, and during search only in studies II and III.

Perception. Table 4 shows the effects of boron intake on Color-name Identification

response times. When contrasted with the high boron intake, low dietary boron resulted in increased response times to identify color names, regardless of presentation color in study III; this effect was not statistically significant when the color name was inconsistent with the presentation color. There were no significant effects of dietary boron on Color-name performance in studies I or II, or on ability to estimate cued time intervals (Time Estimation) in any study.

Memory. Table 5 shows the effects of boron intake on Symbol-Digit and Word Recognition performance. When contrasted with the high boron intake, low dietary boron resulted in increased response times to encode and recall symbol-digit pairings in all three studies, and increased response times to recognize recently presented words in study I. There were no significant effects of dietary boron on error rates for either task in any study. Tasks administered only in study I to assess letter, shape, and cube recognition also showed no significant effects of dietary boron (Table 1).

Discussion and Conclusion

These studies provide converging evidence that relatively short periods (42–73 days) of restricted boron intake can affect brain function and cognitive performance in otherwise healthy older women and men. Two of the three studies described here showed an effect of dietary boron on EEG parameters. The most consistent EEG finding, based on the derived measure of percent-total power, was that low boron intake resulted in a shift toward more activity in the lower frequencies and less activity in the higher, dominant frequencies of the EEG spectrum. This is a particularly important finding, considering that the same effect is often observed in response to nonspecific malnutrition (20,21) and heavy metal toxicity (12,22,23). Increased low-frequency activity is typical of states of reduced behavioral activation (i.e., drowsiness) and mental alertness (24), and has been associated with poorer performance on vigilance and psychomotor tasks (25,26). In addition, decreased higher frequency activity (e.g., α) has been related to impaired memory performance under some conditions (27). Interestingly, a highly similar effect of dietary boron on percent-total power was also observed in the electrocorticograms of mature (200 days) rats fed 0 versus 3 $\mu\text{g/g}$ boron for 75 days (28).

Several other effects of boron intake on EEG parameters were observed which merit further investigation. Coherence was

apparently altered by dietary boron in two studies, but there were some inconsistencies between studies in the location and direction of these effects. Nevertheless, because coherence reflects the degree of physical and functional connectivity between two cortical regions (29), diet-induced changes in coherence would be of great importance. Further, one study showed dietary boron effects on hemisphere asymmetries, alpha reactivity to stimulation (eye opening), and total activity across the frequency spectrum (1–18 Hz). Failure to replicate these effects in the other two studies suggests that these may be weak effects dependent upon the presence of additional, unknown stressors. Dietary copper may have been a factor in the shift from higher- to lower-frequency activity, discussed above, which was observed in the first two, but not the third boron study. The basal diet contained a more abundant amount of copper in the third study. Perhaps the effect of boron on some EEG parameters is dependent on marginal copper intake or status (1).

Behaviorally, low boron intake apparently results in poorer performance on tasks which emphasize psychomotor skills and the cognitive processes of attention, perception, and memory. In the present series of studies, Search-Count, a measure of

attention, and Symbol Digit, a measure of encoding skills and short-term memory, consistently showed effects of dietary boron on response times. However, not all tasks administered showed an effect of dietary boron in all studies. Performance on Tapping, an extremely simple task measuring manual dexterity and fatigue, was impaired by low boron intake in two of three studies. Pursuit, a measure of eye-hand coordination and tracking skills, was impaired by low boron intake in only one study. Low dietary boron increased response times during some conditions of the Color-name Identification task in one study, but not in two others. Low dietary boron also increased response times during a word recognition task, but only in one study. And, of course, performance on several tasks showed no reliable relationship to boron intake (Table 1). Low dietary boron was fed for only 42 days in study I, whereas low boron was fed for 63 days in studies II and III. Perhaps the shorter duration dietary periods were the reason that only 3 of 13 tasks were significantly related to boron intake in study I. Similar to the EEG measures of brain function, the effect of boron on cognitive and psychomotor performance in most instances may also depend on the presence of one or more additional stressors. However, performance

on two tasks, Search-Count and Symbol-Digit, was affected by boron intake in all three studies, which suggests a robust effect of dietary boron on the cognitive processes of attention and memory.

Collectively, the brain electrophysiological and behavioral effects of reduced boron intake on the brain are complementary. Determination of which EEG parameters are reliably sensitive to boron intake and status awaits future study, but measures of the relative activity among frequencies seem to hold the most promise. Future studies must also determine precisely which cognitive processes and psychomotor skills are involved when performance is affected by dietary boron. To understand better boron's relevance to both types of function, future studies must also address the potential importance of additional stressors, dietary and otherwise, which might interact with boron. With this knowledge, a meaningful connection can be made between boron-related changes in brain electrophysiology and those in behavior. In conclusion, the data reviewed in this presentation make a strong case that further study of the effect of boron on brain and behavior is necessary for a complete characterization of the role of boron in human health and function, and may help to determine whether boron is an essential nutrient for humans.

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