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Psychological Effects of Chronic Exposure to 50 Hz Magnetic Fields in Humans Living Near Extra-High-Voltage Transmission Lines

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The validity of several published investigations of the possibility that residential exposures to 50 Hz or 60 Hz electromagnetic fields might cause adverse psychological effects, such as suicide and depression, may have been limited by inadequate controlling for confounders or inadequate measurement of exposures. We investigated the relationships between magnetic field exposure and psychological and mental health variables while controlling for potential confounders and careful characterising individual magnetic field exposures. Five-hundred-and-forty adults living near transmission lines completed neuropsychological tests in major domains of memory and attentional functioning, mental health rating scales and other questionnaires. Magnetic field measurements were taken in each room occupied for at least one hour per day to provide an estimate of total-time-integrated exposure. The data were subjected to joint multivariate multiple regression analysis to test for a linear relation between field exposure and dependent variables, while controlling for effects of possible confounders. Performance on most memory and attention measures was unrelated to exposure, but significant linear dose-response relationships were found between exposure and some psychological and mental health variables. In particular, higher time-integrated exposure was associated with poorer coding-test performance and more adverse psychiatric symptomatology. These associations were found to be independent of participants' beliefs about effects of electromagnetic fields. *Bioelectromagnetics 18:584–594, 1997.* © 1997 Wiley-Liss, Inc.

Key words: cross-sectional study; psychological effects; mental health; electromagnetic fields; powerlines; dose-response

INTRODUCTION

It has been proposed that the central nervous system is sensitive to extremely-low-frequency exogenous electromagnetic fields, possibly because of the electromagnetic character of neuronal transmission [Nair et al., 1989; Cook et al., 1992]. There are also several studies indicating that these fields influence the human central nervous system physiology [Bell et al., 1991; 1992; Cook et al., 1992; Graham et al., 1994; Lyskov et al., 1993a,b]. Behavioral effects also have been observed using measures such as reaction time and response accuracy [Cook et al., 1992; Graham et al., 1994]. Field levels associated with these effects were as small as 6 kV/m (E field) and 10 μT (B field), which are well within the range of environmental human exposures in workplace and residential settings. However, exposure durations in these studies were relatively brief.

Several epidemiological studies have reported associations between residential proximity to high current-carrying 50 Hz or 60 Hz power transmission lines and adverse behavioral effects, including depression [Dowson et al., 1988; Perry et al., 1989; Poole et al., 1993] and suicide [Perry et al., 1981]. However, another study found no association with depression [McMahan et al., 1994]. In all these studies, field exposures either were inferred from assumptions relating exposure level to distance from the source or were based on a single field reading taken at the entrance to the residence. These methods may not result in an

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accurate characterization of actual field exposure history of participants [Kaune et al., 1994]. Also, none of the studies was designed to explore the dose-response relationships between exposure level and the behavioral endpoint under study.

For the study of dose-response relationships between magnetic fields and behavior, the choice of behavioral endpoints is as critical as the choice of appropriate field measures. Environmental toxicology and environmental stress research shows that objective tests of performance and subjective tests of effect may be differentially sensitive to different types of environmental stimuli [Weiss, 1983; Baum et al., 1985; Freudenberg, 1989; Hawkins, 1990], indicating that both should be used.

Our strategy for controlling for the influence of possible confounders was to measure all participant characteristics that were considered capable of influencing performance on the behavioral dependent variables. While previous epidemiological studies have contrasted the performance of groups characterised essentially as ''exposed'' or ''unexposed,'' there are no data from which to derive a rational exposure cutpoint for behavioral effects. Confounding is more likely when simply comparing ''exposed'' and ''unexposed'' persons than when considering a dose-response pattern. For these reasons, we studied the dose-response patterns within a population, all of whom were living near transmission lines.

Psychological and general health measures were chosen on the basis of previous studies in the areas of behavioral toxicology, environmental stress, and general psychological literature [Baum et al., 1982; Weiss, 1983; Hawkins, 1990] and of a pilot study [Beale et al., 1992] that indicated which performance tasks and questionnaires might be most sensitive to environmental variables. Independent variables were chosen on the basis of psychological literature showing that they would exert a significant influence on one or more of the dependent variables chosen and were therefore potential confounders. In contrast to previous epidemiological studies using behavioral endpoints, field exposure was characterised by total time-integrated exposure, an index thought to be adequately representative of participants' overall history of residential exposure [Morgan and Nair, 1992].

METHOD

Topographic maps of the Auckland Metropolitan area were used to locate streets running beneath or beside overhead transmission lines connecting substations in the national grid. 50 Hz magnetic field flux densities were measured at the gateways of houses in these streets, and letters were left in the mailboxes of all houses where gate readings exceeded 0.5 μT. For each such house, another house was selected in the same street with a gate reading less than 0.3 μT. This was to ensure that a wide range of magnetic field levels would be found in the houses to be studied. The letter gave general information about the purpose of the study and invited residents between the ages of 15 and 72 years, who had resided at least six months at that address, to agree to participate by phoning the researcher or by returning a consent form by post.

Participants were recruited at a follow-up visit, during which their status to participate was confirmed and written consent was obtained after any questions had been answered by the researcher. Consent included agreeing to have medical records checked and blood samples taken. This procedure was approved by a university ethics committee. Fifty-five persons consenting initially were not included in the study because they subsequently failed to keep appointments for administration of tests or questionnaires. Forty-nine persons were excluded because they indicated that they would have difficulty being interviewed in English. Twenty-four were excluded because they had resided less than six months at that address, and a further ten, because they were about to change address. Six were excluded for reasons of physical incapacity, and twenty-five, because they were older than 72 years. Of the 704 households approached, 330 declined the invitation to participate. The other 374 households produced a total of 572 participants, 540 of whom met all the inclusion criteria and completed all the questionnaires and tests.

Interviewing and testing was done by senior psychology students under the supervision of qualified psychologists. The interviewers were trained to a mastery criterion on all relevant skills, including making neutral responses to typical questions by participants about the effects of magnetic fields, test and questionnaire administration, and field measurement. Initial interviews were directly supervised by a researcher, and subsequent interviews monitored on a random basis for quality control. Interviews took about 90 min in a quiet area in each participant's home. Interviewers worked in pairs for reasons of personal safety and to facilitate supervision of children during interview of a parent. Interviews included the administration of five tests of attentional skills, two tests of memory for new material, and three questionnaires. These were, in order of administration:

The *Digit Span* subtest from the Weschler Adult Intelligence Scale—Revised [Weschler, 1981]. Subjects are asked to repeat series of numbers read to them, either forwards or backwards. Score is based on errors and longest series correctly repeated.

The *Trail Making Tests A&B* [Lezak, 1983]. The subject must draw lines to connect consecutively numbered circles (part A) or to alternate between numbered and alphabetically lettered circles (part B). Score is time taken to complete.

The *Digit Symbol* subtest from the Weschler Adult Intelligence Scale—Revised [Weschler, 1981]. Subjects transcribe symbols beneath a random series of numbers 1–9, according to a key placed above the series. Score is the number correctly completed in 90 sec.

The *Symbol-Digit Modality Task* [Smith, 1968]. Similar to the Digit Symbol subtest, except that subjects transcribe numbers beneath symbols. In addition to a written version, there is an oral version in which the subject calls out the number that goes with each symbol. Both versions were given. Score is the number correctly completed in 90 sec.

The *d2 Cancellation Test* [Brickencamp, 1975]. The subject must mark each occurrence of a target symbol in each of 14 lines of 20 symbols of similar appearance. Only 20 sec is allowed for each line. Several scores are generated, based on commission and omission errors, percent correct and variability of performance.

The *Selective Reminding Task* [Buschke and Fuld, 1974]. The subject is asked to recall a list of 12 spoken words. After each recall trial the unremembered words are supplied. There are up to 12 recall trials. Several scores are generated, reflecting storage and retrieval processes.

The *Visual Memory Task* from the Weschler Memory Scale—Revised [Weschler, 1987]. In the Visual Memory Forward subtask the subject is required to tap a sequence of identical blocks to imitate a sequence tapped out by the tester. Sequence length is progressively increased. In the Visual Memory Backward subtask the subject must reverse the sequence demonstrated by the tester. Scoring is identical to the Digit Span subtest.

The *Life Changes Questionnaire* [Holmes and Rahe, 1967]. This is a list of 38 life events. Subjects indicate which have occurred in their lives within the past 12 months. The score is the sum of marked events, weighted according to their typical effect on mental health.

The *General Health Questionnaire-28* (GHQ) [Goldberg and Williams, 1988]. This scale requires subjects to indicate on a four-point scale (occasionally—almost every day) how particular statements of attitude or feelings apply to them. Scores on this scale are strongly correlated with professional diagnosis of psychological disorder. Use of the scale to detect ''cases'' of psychological disorder has been validated on a large sample of New Zealand women [Romans-Clarkson et al., 1989]. The standard instructions to respondents were modified slightly in accord with suggestions by the authors to be sensitive to the effect of a chronic, rather than a recent, condition (in this case, magnetic field exposure). In addition to the total score used for ''caseness'' identification, four factor scores (somatic, anxiety, social dysfunction, major depression) are derived from independent subsets of questions.

The *Powerlines Project Questionnaire.* This was developed specifically for this study to collect all relevant demographic, general behavioral and health information. It included questions to determine age, gender, socio-economic status (SES), education, occupation, health problems, medication use, alcohol use, leisure activities (as related to magnetic field exposure), and prior head injuries or other neurological disorders that might impact on current performance of neuropsychological tests. Also included at the end of the questionnaire were two questions requiring self-evaluation. In the first of these, participants were asked to rate their general health over the past six months on a 5-point scale from ''terrible'' to ''excellent.'' In the second, participants were asked to indicate on a 5-point scale from ''definitely made it worse'' to ''definitely improved it,'' how they thought living near a powerline affected their health.

Field Measurements

At the end of the interview, participants were asked to say in which rooms of the house they spent one hour or more per day on average. The estimated time spent in each room was noted. Interviewers then used gaussmeters (MSI-50; Magnetic Sciences International) to record 50 Hz magnetic flux densities at three places in each nominated room. During this time, the normal pattern of appliance use was continued, but no readings were taken closer than 1 metre to appliances. In bedrooms, one reading was recorded at the head of the bed, one in the middle of the bed, and one away from the bed. The time of day when the readings were taken was also recorded.

Because field measurements would be expected to vary to some extent according to variations in current loadings on the transmission lines at various times of the day, seasons of the year, etc., an assessment was made of the representativeness of the field measurements taken following the regular interviews. This was accomplished by a researcher revisiting 38 participants chosen at random and repeating the field measurement

TABLE 1(a). Magnetic Flux Density at 50-Hz: Summary of Measurements for Whole Sample

	Mean	Min	Max	S.D.
Individual reading (μT)	.692	.001	19.430	.902
Room mean (μT)[a]	.692	.001	14.12	.902
Average exposure (μT)[b]	.674	.001	7.580	.808
Time-integrated exposure (μT-hour)[c]	10.014	.003	97.433	12.561

[a] Mean across participants of 3 readings per room; [b] Mean across participants and rooms; [c] Time-integrated exposure (see text).

TABLE 1(b). Exposure Values for Quintiles Based on Time-Integrated Exposure

	Quintiles				
	1	2	3	4	5
Mean average exposure (μT)	.057	.209	.392	.766	1.944
S.D.	(.044)	(.077)	(.103)	(.255)	(.942)
Min.	.001	.080	.183	.322	.771
Max.	.214	.493	.680	1.880	7.580
Mean time-integrated exposure (μT-hour)	.640	2.756	5.333	10.579	30.761
S.D.	(.418)	(.693)	(.937)	(2.246)	(13.766)
Min.	.003	1.489	3.926	7.100	15.110
Max.	1.393	3.893	7.080	15.060	97.433

protocol. The time, day, and month were chosen to suit the participants, without reference to the previous measurement occasion. The local geomagnetic field was measured at six representative locations at the conclusion of the study, using an Elsec 820 proton precession magnetometer (Littlemore Scientific Engineering Co., Oxford, U.K.).

Scoring of Tests and Questionnaires

This was done by researchers from records that did not indicate the address of the participant nor the field measurements taken at the address. Thus the scorer was ''blind'' to the magnetic field exposure relevant to each record.

RESULTS

Because there was some question regarding the validity of using some of the behavioral tests on persons older than 70 or younger than 18, analysis of results was restricted to the 540 participants in the age range 18–70 years.

Magnetic Field Characteristics

The 50 Hz magnetic field flux density measurements are summarised in Table 1(a). Two indexes of average exposure were derived for each participant. *Average exposure* was the arithmetic mean of all readings taken in the two or three rooms in which the participant spent one hour or more per day on average. *Time-integrated exposure* was derived by multiplying the average estimated hours spent in each room by the mean of the readings taken in the room, and summing across the rooms in which the participant spent one or more hours per day on average. The Pearson correlation between the two exposure indexes was .96.

Test-retest reliabilities were calculated as Pearson reliability coefficients for *average exposure* ($r = .915$, $N = 38$) and *time-integrated exposure* ($r = .90$, $N = 38$). The coefficients were calculated on the 38 pairs of values obtained from field measurements and time estimates taken at the first and second visits.

The mean flux density of the local geomagnetic field was 54.4 μT (range 54.3–54.7 μT). Table 1(b) shows values grouped according to quintiles, with 108 participants in each. The quintiles are based on the distribution of time-integrated exposure; however average exposure values for each quintile are also reported because this exposure measure has been widely used in previous studies and is easier to relate to current knowledge about typical environmental exposure levels. Table 2 shows demographic data for the whole sample and for each quintile.

Preliminary analyses were based on the quintile groups shown in Table 3. The reason for this is that a wide variety of outcome measures were being used and there was no a priori reason to assume that the same dose-response pattern would apply to all outcome mea-

TABLE 2. Characteristics of Participants in Whole Sample and Separate Quintiles

	Whole sample	Quintiles 1	2	3	4	5
Female (%)	55	58.0	51.8	45.5	55.4	58.9
Age (mean years)	40.5	43.2	39.2	40.5	42.4	40.2
SES (mean level)	3.63	3.36	3.47	3.72	3.71	3.87
Ethnic identity						
% European	75.4	82.2	76.6	85.0	74.8	58.7
% NZ Maori	10.1	6.5	6.5	7.5	12.1	17.4
% Pacific Island	10.2	9.3	8.4	3.7	10.3	19.3
% Other	4.2	1.9	8.4	3.7	2.8	4.6
Mean duration of residence (years)	10.95	10.5	10.1	9.3	13.3	11.4
Educational level (mean)	1.45	1.59	1.58	1.40	1.37	1.31

SES (socioeconomic status): 1 (high)-7(low); Ethnic identity is self-identified; Educational level: 1 = basic, 2 = university entrance, 3 = tertiary qualification.

sures. We therefore initially examined the mean outcome scores for each exposure quintile before performing linear regression analyses on the individual data.

Regression Analyses

Multiple regression analyses were carried out separately on two data sets, one incorporating all the neuropsychological tests and the other incorporating the self-reported general health and psychological health measures. Univariate regressions on average exposure and time-integrated exposure were followed by joint multivariate multiple regressions on both average exposure and time-integrated exposure to adjust for possible confounders. The programme used (SAS) generates a multivariate statistic which tests the legitimacy of subsequent univariate analyses, in regard to the possibility of experiment-wise Type-I error. The multivariate F was significant in each case. The multiple regression analyses included the additional independent variables: age, gender, socioeconomic level, and life changes. Finally, additional multiple regression analyses were conducted to examine the effects of controlling for self-rated health and perceived effect of powerlines on personal health. Although these two variables were not necessarily confounders, it is conceivable that they could mediate the effects of exposure on behavioral variables. Results of these analyses are summarised in Table 3.

The body of Table 3 shows mean scores for each quintile and the regression statistics, for each dependent variable. The ‘‘crude’’ regression coefficient is that obtained by regressing the dependent variable on time-integrated exposure alone, whereas the ‘‘adjusted’’ regression coefficient is obtained from the multiple regression that included the possible confounding variables: gender, age, socioeconomic status, and life changes.

The data in Table 3 show that, of all the neuropsychological variables, only Digit Symbol was significantly predicted by time-integrated exposure (regression coefficient = −.011, 95% CI .019—.0034, P = .0035). The unadjusted quintile means indicate that the detrimental effect of exposure on the Digit-Symbol test performance is confined largely to the 5th quintile of time-integrated exposure.

Although mean scores on self-rated health decreased systematically between the 2nd and 5th quintiles (5 = excellent health, 1 = terrible health), there is the opposite trend between the 1st and 2nd quintiles. Linear regression indicates that time-integrated exposure is not a significant predictor of self-rated health (regression coefficient = −.00026, 95% CI .00087−.00035, P = 0.40).

A similar dose-response function is shown by the GHQ scores, with an increasing trend in scores (more adverse symptoms) between the 2nd and 5th quintiles, but the opposite trend between the 1st and 2nd quintiles. The regression analysis shows that adverse symptoms tend to increase with increasing exposure (regression coefficient = .006, 95% CI .0025−.0095, P = 0.0012). GHQ scores can be used to identify ‘‘cases’’ having a defined level of psychological disorder; the number of cases is shown for each quintile, using a relatively stringent criterion unlikely to identify false positives (cutpoint score 11/12) [Romans-Clarkson et al., 1989]. The number of cases so identified in each quintile is shown in Table 3. In this instance the function is monotonic; The odds ratios for GHQ ‘‘caseness’’ for each of the five quintiles are 1.0, 1.2 (95% CI 0.4−3.3), 1.5 (95% CI 0.5−4.0), 1.6 (95% CI 0.6−4.4), and 2.1 (95% CI 0.8−5.5).

TABLE 3. Mean Values (Standard Deviations in Parentheses) for Quintiles on Neuropsychological Test Measures and Health Questionnaires, and Statistics from Regression Analyses

	Quintile means and standard deviations					Regression statistics			
Neuropsychology test measures	1	2	3	4	5	Unadjusted reg. coef.	Adjusted reg. coef.	95% confidence interval (CI)	*P*
Headaches	1.00 (0.72)	0.94 (0.68)	1.00 (0.73)	1.09 (0.73)	1.15 (0.73)	0.00042	0.00022	−0.00025, 0.00069	0.35
Digit span total	14.34 (3.19)	14.93 (3.83)	14.98 (3.97)	15.06 (3.66)	14.29 (3.46)	−0.00095	−0.00024	−0.0026, 0.0021	0.84
Visual memory span	15.6 (3.27)	15.8 (3.45)	15.29 (2.93)	15.82 (2.96)	15.84 (3.05)	0.0010	0.0011	−0.00086, 0.0030	0.24
Selective memory LT	10.69 (2.19)	10.97 (2.04)	11.00 (2.07)	10.73 (2.10)	11.06 (1.67)	0.0008	0.00072	−0.00057, 0.0020	0.27
Selective memory CR	3.11 (1.00)	3.37 (0.91)	3.15 (1.10)	3.13 (1.26)	3.13 (0.92)	−0.00032	−0.00044	−0.0011, 0.00023	0.19
D2 missed targets	138.33 (38.22)	135.64 (40.77)	140.30 (40.07)	138.67 (38.45)	141.00 (40.17)	0.0051	0.0045	−0.019, 0.028	0.71
D2 false alarms	4.07 (7.20)	4.19 (7.75)	4.17 (6.78)	4.00 (6.88)	3.13 (3.63)	−0.0025	−0.004	−0.0086, 0.00040	0.07
Trail making A	33.15 (11.17)	31.64 (12.87)	30.91 (11.90)	31.67 (11.82)	31.66 (11.93)	−0.0036	−0.0038	−0.011, 0.0034	0.30
Trail making B	74.4 (28.05)	74.38 (31.43)	74.98 (32.06)	71.11 (29.03)	70.5 (27.6)	−0.0128	−0.014	−0.031, 0.0038	0.10
Symbol-digit W	46.93 (11.50)	49.94 (10.55)	47.40 (10.62)	47.25 (11.80)	46.33 (11.95)	−0.0033	−0.0022	−0.0085, 0.0041	0.48
Symbol-digit O	55.88 (12.84)	55.76 (12.61)	53.11 (13.14)	55.64 (13.20)	54.87 (13.33)	−0.0017	−0.0016	−0.0090, 0.0058	0.66
Digit-Symbol	53.4 (12.56)	53.96 (13.27)	52.91 (12.36)	53.79 (15.30)	49.60 (15.27)	−0.0084	−0.011	−0.019, −0.0034	0.0035**
Health Measures									
GHQ total	4.05 (5.30)	3.18 (4.86)	3.64 (5.21)	4.5 (5.46)	5.54 (7.04)	0.0080	0.0060	0.0025, 0.0095	0.0012**
GHQ somatic	12.57 (3.77)	12.00 (3.59)	12.60 (3.95)	13.76 (4.20)	13.56 (4.37)	0.0049	0.0037	0.0011, 0.0062	0.0048**
GHQ anxiety	13.02 (4.19)	12.00 (3.90)	12.02 (4.13)	13.27 (4.17)	14.63 (10.62)	0.0073	0.0057	0.0018, 0.0096	0.0056**
GHQ social	13.18 (2.68)	13.33 (2.79)	13.55 (3.16)	13.36 (2.87)	13.40 (3.06)	0.00055	0.00053	−0.0014, 0.0025	0.59
GHQ depression	8.88 (3.49)	8.56 (2.57)	8.58 (3.02)	8.96 (3.21)	9.54 (3.95)	0.0035	0.0026	0.00044, 0.0047	0.019*
Self-rated health	3.68 (0.78)	4.00 (0.84)	3.92 (1.03)	3.68 (1.06)	3.65 (1.03)	−0.00054	−0.00026	−0.00087, 0.00035	0.40
GHQ ''CASES'' (frequency)	7	8	10	11	14				
Perceived effect	2.27 (0.57)	2.29 (0.47)	2.21 (0.58)	2.34 (0.58)	2.45 (0.70)	0.00068	0.00055	0.00016, 0.00094	0.0067**

* = significant at 0.05 level. ** = significant at 0.01 level. Reg. coeff. = regression coefficient.
Selective memory LT = selective reminding test long term store, Selective memory CR = selective reminding test consistent retrieval, Symbol digit W = symbol digit modalities written, Symbol digit O = symbol digit modalities oral, GHQ total = General Health Questionnaire-28 standard scoring, GHQ somatic = GHQ somatic factor (Likert scoring), GHQ anxiety = GHQ anxiety factor (Likert scoring), GHQ social = GHQ social dysfunction factor (Likert scoring), GHQ depression = GHQ depression factor (Likert scoring), GHQ ''CASES'' = number of cases identified using 11/12 cutpoint, Self-rated health = self-rated health last 6 months, Perceived effect = perceived effect of powerline on own health.

The GHQ incorporates four factors based on independent sets of questions: somatic symptoms, anxiety, social dysfunction, and major depression. Mean scores on these factors for each quintile are shown in Table 3. Also shown are the regression summary statistics for each factor, which indicate that exposure level predicts scores on 3 of the 4 factors: Somatic, anxiety, and major depression (regression coefficients all significant, $P < 0.02$). Scores on the other factor, social dysfunction, were uninfluenced by exposure (regression coefficient = .00053, 95% CI .0014–.0025, $P = 0.84$). As indicated by the positive sign of the regression coefficients for the three affected factors, increasing exposure was associated with increasing levels of adverse symptomatology.

We explored the effect of adding two additional variables to the group of predictors used in the multiple regression analyses. The variables chosen were self-rated health and perceived effect of powerlines. Both were hypothesised to be dependent variables predicted by time-integrated exposure, but a case could be argued that either variable could modulate the influence of time-integrated exposure on other dependent variables in a way that would make them potential confounders. Table 4 shows the effect of controlling for these variables on the regression coefficients for time-integrated exposure for those dependent variables for which exposure was found to have significant predictive power.

Considering first those GHQ variables that were predicted by time-integrated exposure, adding self-rated health to the regression variables was accompanied by a small reduction in the associated regression coefficients for time-integrated exposure: 13% (somatic); 8.7% (anxiety); 15.3% (depression). Adding perceived effect of powerlines gave larger reductions in the regression coefficients for time-integrated exposure: 40.5% (somatic); 22.8% (anxiety); 38.46% (depression). On the other hand, the predictive power of time-integrated exposure on Digit-Symbol test scores was affected little by adding either self-rated health (0%) or perceived effect of powerlines (10%) to the regression variables.

DISCUSSION

Magnetic-Field Characteristics

The range of average exposures of participants, as indicated by the average exposure data in Table 1(a), confirms that the study achieved the goal of sampling a sufficiently wide range of exposure levels to test the hypothesis of a linear dose-response function over a representative range of ambient environmental exposures. The range sampled extends from typical low residential levels to the higher levels more typical of occupational exposure [e.g., Kaune et al., 1984; Sahl et al., 1994; Bracken et al., 1995].

Because the flux density of magnetic fields fluctuates according to the current carried in the conductor,

TABLE 4. Regression Coefficients and Associated Statistics for Time-Integrated Exposure in Multiple Regression Analyses of Selected Dependent Variables

Variable	Unadjusted reg. coef.	Adjusted reg. coef.	Adjusted + self-rated health reg. coef.	95% CI	*P*	Adjusted + perceived effect reg. coef.	95% CI	*P*
GHQ total	.0080	.0060	.0050	.0021, .0083	.0012**	.0035	.00036, .0066	.029*
GHQ somatic	.0049	.0037	.0032	.0010, .0054	.0058**	.0022	−.00015, .0046	.069
GHQ anxiety	.0073	.0057	.0052	.0016, .0090	.0084**	.0044	.00048, .0083	.027*
GHQ social	.00055	.00053	.00025	−.0016, .0021	.78	−.00037	−.0022, .0015	.69
GHQ depression	.0035	.0026	.0022	.00024, .0042	.029*	.0016	−.00036, .0036	.12
Digit symbol	−.0084	−.011	.0039	−.019, −.0034	.0044**	−.010	−.017, −.0024	.0024**

* = Significant at .05 level. ** = Significant at .01 level.

CI = Confidence interval, Reg. coef. = Regression coefficient, GHQ total = Total score on GHQ-28, GHQ somatic = GHQ Somatic factor (Likert scoring), GHQ anxiety = GHQ anxiety factor (Likert scoring), GHQ social = GHQ social dysfunction factor (Likert scoring), GHQ depression = GHQ depression factor (Likert scoring), Digit-symbol = digit-symbol test, self-rated health = self-rated health last 6 months, perceived effect = perceived effect of powerline on own health.

there is a concern that field measurements taken on only one occasion might not be adequately representative of the average level over the day, week, or month. For example, fields arising from the current in transmission lines varies somewhat according to demand at the substations supplied by the lines. Details available to us on current loadings in the lines relevant to our study were insufficient to calculate the likely discrepancy between our measurements and the ''true'' average exposure of each participant over the previous six months. However, the test-retest reliability coefficients obtained for the remeasured sample indicates that the single measurement occasion used in the study was reasonably representative of the whole time of interest, accounting for about 80 percent of the variance between measurement occasions (average exposure; $r = .915$). Overnight field exposures were not measured, but theoretically this would be expected to decrease, rather than increase, the likelihood of finding a systematic effect of exposure.

Occupational and other sources of non-residential exposure were not measured and are assumed to be equivalent across quintiles. If this assumption is incorrect and other sources of exposure are confounders, the results relating exposure to psychological variables are not invalidated, but are no longer confined just to residential exposure. The flux density of the local geomagnetic field (54.4 μT) was measured because of the recent speculation that particular combinations of geomagnetic and AC field strength may be critical for the obtaining of some biological effects (e.g., Liboff and McLeod, 1995).

Effects of Magnetic Field Exposure on Behavioral Measures

The main aim of the study was to test the hypothesis that time-integrated magnetic field exposure would predict performance on behavioral tests of memory and attention and would predict scores on mental health measures. In particular, it was hypothesised that there would be a significant linear function relating magnetic field exposure to psychological and mental health variables.

Association Between Exposure and Neuropsychological Test Performance

Neither the simple regression nor multiple regression analyses showed evidence that time-integrated magnetic field exposure, as represented by time-integrated exposure, predicted performance on tests of memory or attention other than the Digit-Symbol test. Lower scores on the Digit-Symbol test were predicted by higher time-integrated exposure values, even after regression coefficients were adjusted for the effects of possible confounders.

Why was this test affected while others were not? This test is regarded as unaffected by differences in intellectual prowess, but memory of learning, abilities such as motor persistence, sustained attention, response speed and visuomotor coordination play important roles [Lezak, 1983]. Of all the subtests in the WAIS-R Intelligence Test, this is the most sensitive to the effects of brain damage. The test is speeded, that is, there is a time limit and speed is emphasised in the instructions. In terms of the load placed on mental information-processing capacity, this test is among the most demanding of those given.

It is notable that the adjustment of the regression coefficient for presumed confounders had little effect. On the other hand, age, gender and socio-economic status all were significant determiners of performance on this test, consistent with other evidence that performance is strongly influenced by these variables [Lezak, 1983]. It is notable that the Digit-Symbol test has been found to be one of the most sensitive indicators of undifferentiated brain damage [Lezak, 1983] as well as being a particularly sensitive measure of neurological effects of toxin exposure [Hanninen, 1983]. However, because the Digit-Symbol test was not given special status by any a priori hypotheses, the results can only be considered to be weakly supportive of the interpretation that cognitive function is adversely affected by exposure.

Association Between Exposure and Perceived Effect of Powerlines

Self-rating of the perceived adverse effect of powerlines on health increased with increasing time-integrated exposure, even after adjustment for confounders. One interpretation of this is that participants had an implicit awareness of their exposure level and also believed that higher exposure levels had a more detrimental effect than lower exposure levels on health. This is implausible, on the grounds that all the participants lived near the powerlines and probably had little idea of the factors that jointly determine their exposure as individuals to the magnetic fields arising from the lines [Delpizzo, 1990; Cook et al., 1992]. Although participants might accurately estimate their distance from a powerline, the strength of the magnetic field is determined by the square of this distance, in combination with other factors such as line geometry and current loading [Kavet et al., 1992]. Furthermore, because perceived effect correlated better with time-integrated exposure than with average exposure, participants would also need to be able to incorporate time-integra-

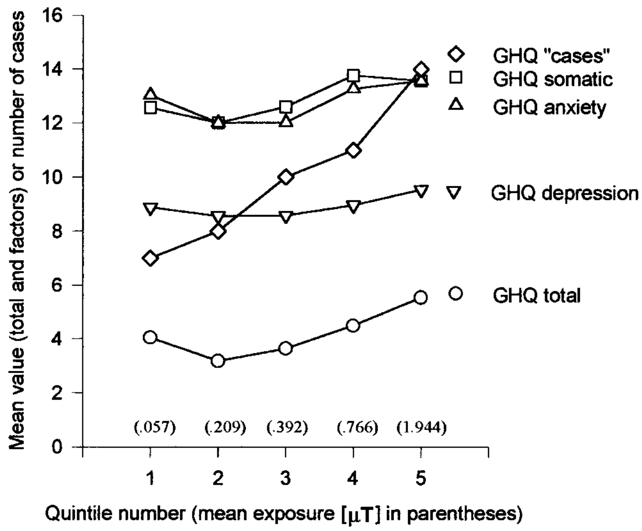

Fig. 1. For each quintile of time-integrated exposure, the mean score is shown for all GHQ variables showing significant trends. The number of GHQ ''cases'' is also shown. Average exposure levels for each quintile are shown below the X axis.

tion into their concept of exposure for the effect to be explainable simply as a conscious projection of their beliefs.

Our preferred interpretation is that this relationship results from awareness by participants of their state of health, together with a willingness to hold the powerlines partly responsible. This is consistent with the observation that mental health scores were significantly predicted by time-integrated exposure, and that time-integrated exposure, perceived effect and GHQ were significantly intercorrelated.

Association Between Exposure and Mental Health Measures

The overall GHQ score and the scores on three of the four GHQ factors (somatic symptoms, anxiety, and major depression) were all found to increase with increasing time-integrated exposure. For each measure, there was a significant linear dose-response function both before and after adjustment for confounding influence of age, gender, socioeconomic level, and life changes. When the overall GHQ score was used to identify ''cases'' of clinically significant psychological illness, the prevalence of cases was found to increase monotonically with time-integrated exposure. For the quintile with the highest exposure, the prevalence of cases among women was five times that that predicted on the basis of a New Zealand study of 2000 women [Romans-Clarkson et al., 1989], indicating a significant excess risk for mental health problems in the high exposure group ($\chi^2 = 13.5$, $P = .0002$). The mean exposure level (mean average exposure value) for this quintile was 19.44 mG, and the minimum and maximum were 7.71 mG and 75.8 mG, respectively. This exposure is greater than that reported elsewhere to be associated with increased incidence of depression [Perry et al., 1989 − mean 2.26 mG] or with suicide [Perry et al., 1981 − mean 0.87 mG]. It is also greater than the mean value (4.86 mG) and range reported in a study of women living near a transmission line who were found not to have an excess risk of depression [McMahan et al., 1994].

The GHQ factor scores represent dimensions of symptomatology [Goldberg and Williams, 1988]. For example, the somatic factor reflects concern about general physical health (e.g., ''felt that you are ill?'') as well as specific problems (e.g., been getting any pains in your head?''). The anxiety factor focuses on worry, sleep problems, irritability, and tension. The depression factor reflects poor self-esteem, hopelessness, and suicidal thinking. The social disfunction factor is about uselessness, ineffectiveness, indecision, lack of enjoyment, or accomplishment. Of these factors, depression has most often been considered as influenced by magnetic field exposure, although a wider range of psychiatric disorder has been implicated in a few studies, particularly irritability and sleep problems [Asanova and Rakov, 1974; Shandala et al., 1984]. The present results indicate the desirability of including measures of psychiatric disorder other than major depression, because anxiety and somatic symptoms are at least as strongly associated with magnetic fields as are depressive symptoms.

A dose-response relationship generally is regarded as a desirable criterion for the demonstration of causation in toxicology research [Kramer, 1988]. Commentaries on this issue have referred to evidence from animal studies that the usual toxicology model characterised as ‘‘more is worse’’ may not be appropriate for electromagnetic fields because some biological effects appear to be ‘‘windowed’’ with respect to both frequency and intensity of the field [Nair et al., 1989; Frey, 1990; Morgan et al., 1995]. Morgan and Nair (1992) have advised that account be taken of alternative possible ‘‘effects functions’’ describing the relationship between field parameters and biological effects.

Consideration of dose-response functions in this study has been facilitated by plotting of the relevant values from Table 4 into Figure 1. The trends across quintile means for the significant dependent variables suggests a reversal, below the 2nd quintile, of the predominant, statistically significant linear relationship found across the whole range of time-integrated exposures. This might indicate that the data would fit better to a curvilinear model. However, no function of this shape has yet been proposed on theoretical grounds. Also, it is notable that the quintile means are unadjusted for possible confounders and therefore do not accurately represent the effect function for field exposure alone. Unlike the overall GHQ total score and the GHQ factors, the function for GHQ ‘‘cases’’ is apparently monotonic.

There remains the question of whether the results represent effects of ‘‘acute’’ exposure, that is, exposure present at the time of interviewing and testing, or ‘‘chronic’’ exposure, the cumulative effect of exposure over months or years. The fact that time-integrated exposure was a better predictor of the psychological variables than was average exposure, also indicates that the effects were related to exposure history rather than acute exposure at the time of interviewing and testing.

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