First-year Statistics for Psychology Students
through Worked Examples

6. Analysis of Variance

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Any remaining errors or omissions are my responsibility. I would be pleased to receive information from anyone who spots any error, mathematical or otherwise. I can be contacted via e-mail at:

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I should also be pleased to hear from anyone who finds this tutorial helpful, either for themselves or for their students.

Charles McCreery

General Introduction[1]

There are usually three complementary methods for mastering any new intellectual or artistic task; these are, in ascending order of importance:

- reading books about it
- observing how other people do it
- actually doing it oneself

These tutorials focus on the second of these methods. They are based on handouts that I developed when teaching first-year psychology students at Magdalen College, Oxford. The core of each tutorial is a worked example from an Oxford University Prelims Statistics examination paper. I have therefore placed this section in prime position; however, in teaching the order of events was different, and more nearly corresponded to the three-fold hierarchy of methods given above:

1. Students were invited to read one of the chapters on the Recommended Reading list, given at the end of each tutorial. They were also expected to attend a lecture on the topic in question at the Department of Experimental Psychology.

2. Students would attend a tutorial, in which we would go through the worked example shown here. They would take away the handouts printed as Appendices at the end of each chapter, which were designed to give structure to the topic and help them when doing an example on their own.

3. They would be given another previous examination question to take away and do in their own time, which would be handed in later for marking.

I am strongly in favour of detailed worked examples; following one is the next best thing to attempting a question oneself. Even better than either method is doing a statistical test on data which one has collected oneself, and which therefore has some personal significance to one, but that is not usually practicable in a first-year course.

I list three books in the General Bibliography at the end of this tutorial which give worked examples. One of these is Spiegel (1992), in which

[1] This is a general introduction to a series of six tutorials on topics in statistics, available here: http://www.celiagreen.com/charlesmccreery.html

each chapter has numerous ‘solved problems’ on the topic in question. These worked problems occupy more than half of each chapter. However, the solutions to the individual problems are not as detailed and discursive as the ones I give here.

Another book which is based on worked examples on each of the topics covered is Greene and D’Oliveira (1982), also listed in the General Bibliography. Their examples are as detailed as those I give here. However, they do not cover probability and Bayes’ theorem or Analysis of Variance.

Finally, I strongly recommend the *Introductory Statistics Guide* by Marija Norusis, designed to accompany the statistical package *SPSS-X*, and based on worked examples throughout. Even if the student does not have access to a computer with the *SPSS-X* package on it, this instruction manual contains excellent expositions of all the basic statistical concepts dealt with in my own examples.

Analysis of Variance

Contents

1. Introduction

In this worked example of a two-way ANOVA the arithmetical workings are set out in the most explicit way possible for heuristic purposes (i.e., the objective is to show as clearly as possible what is going on). In practice, various short-cut methods of calculation are possible, particularly in an examination context.

Appendix 1 summarises some points concerning repeated measures and interaction effects. These are topics which are not directly involved in the particular worked example in this tutorial, although the concept of repeated measures is alluded to. However, the Appendix may be useful to people learning about other forms of the ANOVA.

Recommended reading

The present tutorial will probably be found more useful if some preliminary reading around the topic has already been done. It does not matter if not everything in the reading is clear on the first go through. After the preliminary reading you can work through the example in the present tutorial and then return to the books, when you may have a better feel for the topic.

I particularly suggest that it is important not to get bogged down in trying to understand the details of areas of the topic which may not be relevant to one's syllabus. Some of the books mentioned below go into the subject in great depth, and with a degree of detail which is probably unnecessary for the purposes of most examinations.

For the purposes of understanding what is going on in a two-way ANOVA I particularly recommend following the worked example given on pp. 355-357 of Murray Spiegel's book listed below. The arithmetical workings are laid out very explicitly, with a minimum of abstract notation. In my view going through an explicit worked example of this kind can give the student a better understanding of the underlying theoretical basis of ANOVA than listening to a verbal exposition.

Hoel, Paul G. (1976). *Elementary Statistics* (4th edition). New York: Wiley. Chapter 11.

Covers one-way and two-way ANOVAs in a relatively user-friendly manner.

Howell, David C. (1997). *Statistical Methods for Psychology* (4th edition). London: Duxbury Press. Chapters 11-14.

There are nearly 200 pages on ANOVA in these four chapters, covering all aspects of the subject, including repeated measures designs.

Hays, William L. (1994). *Statistics* (5th edition). Orlando, Florida: Harcourt Brace. Chapters 10-12.

More than 200 pages in this case. Similar in comprehensiveness to Howell.

Spiegel, Murray R. (1992). *Schaum's Outline of Theory and Problems of Statistics* (2nd edition). New York: McGraw-Hill. Chapter 16.

The theoretical introduction to this chapter is compressed, but the worked examples in the remainder may be helpful.

2. The question[2]

(i) What is meant by *randomisation*?

An undesirable effect of some antihistamines is drowsiness, which is a consequence of the effect of the drugs on the central nervous system. These data come from an experiment of Hedges, Hills, Maclay, Newman-Taylor and Turner (1971) to compare the effect on the central nervous system of a placebo and two antihistamines. This was done by measuring the *flicker frequency*[3] some time after drug administration in four volunteers who have taken the three treatments. The data presented here are scaled measures based on the flicker frequency.

Subject Number	Meclastine	Promethazine	Placebo
1	112	112	131
2	48	37	61
3	106	93	112
4	51	46	70

(ii) Plot these data in a meaningful way and comment.

(iii) Carry out an appropriate analysis to examine whether there is a difference between the effects of the different drugs, stating clearly your hypotheses, conclusions and any assumptions made.

(iv) State two precautions which should have been taken in running this experiment.

(v) Give two benefits which would have resulted if more than one measurement for each drug for each subject had been obtained.

[The *flicker frequency*, often referred to as the *critical flicker frequency* or CFF, is that frequency at which a flickering light appears to a particular observer to be continuous rather than discontinuous. It is usually estimated by taking a series of readings from both below and above; that is to say, the experimenter starts with a frequency below the fusion point and gradually increases it until the flicker disappears; he/she then starts again from a frequency above the fusion point and lowers the frequency until the flicker appears again. The CFF reading for a given subject at a given time would then be the mean of several observations taken in both directions, to allow for 'noise'.]

[2] The question is taken from the Prelims Statistics paper for first-year psychology students at Oxford University, Hilary Term, 1999.

3. The answer

3.1 What is meant by randomisation?

Random sampling: a sample is said to be taken at random from a population when each member of the population has an equal chance of being chosen. One result is that each member would be selected approximately the same number of times as any other member, given a large number of repetitions of the experiment.

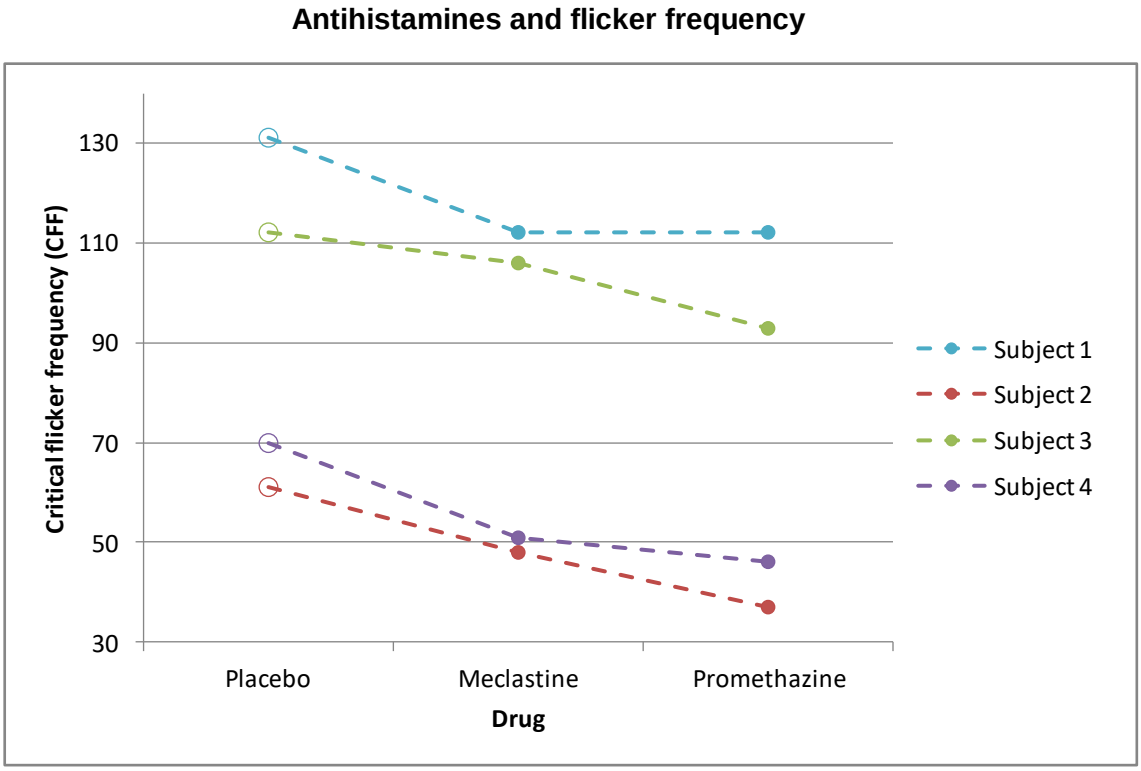
The concept of *randomisation* in the design of experiments is a distinct but related concept. It refers to the process of allocating each member of the population being studied to one of a number of possible experimental conditions, or 'treatment groups', by some chance process such as the use of random number tables. Assuming that we wish to have an equal number of subjects in each group, the chances of a given subject being allocated to each of the possible conditions are thus equal.

The purpose of random allocation of this kind is to produce treatment groups that are as nearly similar as possible prior to the experimental procedure whose effect it is desired to measure. Thus any difference between the groups subsequent to the treatment may be attributed to the experimental treatment and not to some systematic, prior difference between them.

Random allocation also serves the purpose of precluding any bias, conscious or unconscious, on the part of the experimenter, who may have a vested interest in a particular experimental outcome.

If the experiment takes the form of each subject being subjected to several different treatments at different times, then the order of the different treatments may be randomised for each subject, to control for the possibility of one treatment potentiating or diminishing the effect of a later treatment.

3.2 The plot



Comment on the plot:

The most notable effect appears to be large individual differences in baseline critical flicker frequency. We infer this from the fact that Subjects 1 and 3 occupy widely differing positions on the *y*-axis of the chart from subjects 2 and 4. The relative positions on the *y*-axis of the four subjects are maintained under all three conditions, Placebo, Meclastine and Promethazine.

It also appears that both antihistamines have the effect of depressing the CFF, since the highest mean value in all four subjects is for the placebo condition. Promethazine would appear to depress it more than Meclastine, though this difference may not be statistically significant, given the small number of subjects.

[The data are consistent with the idea that the critical flicker frequency is a measure of sensory efficiency, and hence of cortical arousal.]

3.3 The ANOVA analysis

We will perform a repeated measures ANOVA on the data to determine whether there is any significant difference between the effects of the three different treatments. There will be two factors in this analysis: 'Drug', which has three levels (i.e., Meclastine, Promethazine and Placebo); and 'Subject', which has four. The inter-subject variability referred to above suggests that there may be a significant effect for Subject. Whether the intra-subject variability is sufficient to give us an effect for Drug is less clear.

3.3.1 Hypothesis and assumptions

The hypothesis is that the two antihistamines depress cortical arousal, and hence visual efficiency as measured by the visual system's power of temporal resolution. We predict that CFF will therefore be significantly lower under the influence of the antihistamines than under the placebo condition.

The *null hypothesis* is that CFF does not vary significantly with the factor 'Drug'. This would imply that antihistamines do *not* significantly depress visual performance. Therefore, we hope to see results that allow us to *reject* the null hypothesis with high probability.

Our assumptions are: (1) that the observations under each condition are drawn from a normal distribution, even though there are too few under each condition to constitute a normal sample; and (2) that the variances of each of these underlying normal distributions are approximately equal.

[These are general assumptions underlying all applications of the ANOVA test. Note that the question explicitly mentions that the data are from 'scaled measures'; i.e. they are at least interval data, so a parametric test such as ANOVA is appropriate.

For an explanation of the distinctions between interval and other types of measurements, and the implications for what type of test to use on a given type of data, please refer to Appendix 2.]

3.3.2 Computation of the ANOVA

[The purpose of an ANOVA analysis is to enable us to ascribe the overall variability of a set of data to a number of different sources.

Mathematically speaking, we are aiming to *partition* the 'sum of squares'[4] of a data set into different components.

In this case, we are looking at three possible sources of variability:
(a) the effect of Drug (which in this case includes Placebo)
(b) the effect of Subject
(c) any remaining sources of variability, collectively referred to as 'error'.

Note that the term 'error' here does not imply any sort of mistake. In another context the error variation might be of interest to us. Some of it might be due to a time of day effect, for example, if the subjects were not all run at the same time of day.

We begin by calculating row means, column means and the 'grand mean', which is the mean of every single data point, in our table below.]

Subject number	**Meclastine**	**Promethazine**	**Placebo**	**Row mean**
1	112	112	131	**118.33**
2	48	37	61	**48.67**
3	106	93	112	**103.67**
4	51	46	70	**55.67**
Column mean	**79.25**	**72**	**93.5**	

Grand mean = (112 + 48 + 106 + 51
+ 112 + 37 + 93 + 46
+ 131 + 61 + 112 + 70) / 12
= 979/12
= 81.58

[4] Note that the phrase 'sum of squares' refers to the sum of squared deviations from a mean, not the squares of the data values themselves.

A. Total variability

[We now need to work out the total amount of variation in the data. We therefore calculate 'total sum of squares' (TSS), as follows:]

Observation	Deviation of observation from grand mean (= 81.58)	Deviation squared
112	30.42	925.38
48	-33.58	1,127.62
106	24.42	596.34
51	-30.58	935.14
112	30.42	925.38
37	-44.58	1,987.38
93	11.42	130.42
46	-35.58	1,265.94
131	49.42	2,442.34
61	-20.58	423.54
112	30.42	925.38
70	-11.58	134.10
	Total sum of squares (TSS):	**11,818.92**

[The calculation of TSS is laid out in the explicit form above for heuristic purposes. In practice you are likely to be able to use a short-cut method for calculating the TSS. For example, in the Oxford University Psychology Prelims examination the student is allowed the use of a calculator. The TSS can be calculated by entering all 12 observations into the calculator, working out their standard deviation (SD) and squaring the SD to get the variance. Having got the variance, you can derive the TSS by multiplying the variance by $(n - 1)$, where n is the total number of observations

N.B. There are two distinct definitions of variance (and hence of SD, its square root). If we are calculating the variance of a *population*, we divide TSS by N, the total number in the population; but if we are dealing with a *sample*, it is normal to divide by $(n - 1)$, where n is the total number in the sample. (This is an adjustment designed to allow for *sampling error* in our data, or random variation from sample to sample. See Appendix 2.)

If using a calculator, therefore, it is advisable to be aware of which version of SD you are calculating.]

B. Column calculations

[In order to determine the degree of variability due to Drug, we next calculate the 'Column Sum of Squares'.]

Column means	Deviation of column mean from grand mean (=81.58)	Deviation squared
79.25	-2.33	5.43
72.00	-9.58	91.78
93.50	11.92	142.09
	TOTAL:	**239.30**

Column Sum of Squares (CSS)

= Sum of squares of column mean deviations × No. of rows

= 239.30 × 4

= 957.20

[Note that the sum of squared deviations of column means, shown at the foot of the third column, is equivalent to the variation in just *one* row of data values, albeit a representative one. To get an estimate of the *total* variation due to the 'column factor', Drug, we have to extrapolate this variation across the whole two-dimensional array of columns; hence the need to multiply by the number of rows.

As with the computation of the TSS, the calculation of the CSS shown above is laid out in a manner designed to show the underlying rationale of ANOVA. In an examination in which a calculator is permitted, you can calculate the CSS by entering the three column means, getting the result for SD and multiplying by the number of columns minus 1, i.e.: $c - 1 = 2$.]

C. Row calculations

[In order to determine the degree of variability due to Subject, we now calculate the 'Row Sum of Squares'.]

Row means	Deviation of row mean from grand mean (=81.58)	Deviation squared
118.33	36.75	1350.81
48.67	-32.91	1083.29
103.67	22.09	487.82
55.67	-25.91	671.50
	TOTAL:	**3592.93**

Row Sum of Squares (RSS) =

Sum of squares of row mean deviations × No. of columns

= 3592.93 × 3

= 10,778.79

[This time we are multiplying the sum of squared deviations of the *row* means by the number of *columns*, for an analogous reason to that given above for multiplying the sum of squares of the column means by the number of rows.

Note that RSS has a substantially higher value than CSS, reflecting the fact that, as noted simply from visual inspection of the data, there seems to be more variability from one subject to another than within-subject variability due to the different effect of different drugs.]

As with the CSS, a calculator can be used to work out RSS from the SD of the four row means.]

D. 'Error' calculations

[Finally, we calculate the residual degree of variability, due neither to Drug effects nor to Subject effects. This is 'Error Sum of Squares'.]

Error sum of squares (ESS):

$$\begin{aligned} ESS &= TSS - RSS - CSS \\ &= 11{,}818.92 - 10{,}778.76 - 957.20 \\ &= 82.96 \end{aligned}$$

[In an experimental design of this sort there are only two sources of variation in the flicker frequency readings which are of interest to us: variation associated with different drugs (i.e. between-groups variation), and variation associated with different subjects (i.e. within-groups variation). So if we know the value of the total variation and the value of both these two sorts of variation, then 'error variation' is simply what is left over when we have subtracted both sorts from the total.

The 'error' term in this case is small relative to the main effects for Subject and Drug. An intuitive explanation for this can be seen from the plot: the pattern of variation due to drug is similar in each subject, so that by the time one has taken out the variation in the scores due to drug and that due to subject, the effect of any other factor appears to be minimal.]

E. Computation of mean squares

[We next need to calculate the mean squares from the sums of squares.

> "mean squares […] represent the calculated amount of variance attributable to each source of variance."
> (Greene & d'Oliveira 1982, p.94)

In order to do this we need to know the degrees of freedom for each source of variance. These are in each case equal to the number of possible values minus 1.]

Total:

$$\begin{aligned} \text{Degrees of freedom (DF)} &= (r \times c) - 1 \\ &= (4 \times 3) - 1 \\ &= 12 - 1 \\ &= 11 \end{aligned}$$

Rows:

$DF_R = r - 1$

$= 4 - 1$

$= 3$

Columns:

$DF_C = c - 1$

$= 3 - 1$

$= 2$

Error:

[The DF for the error variance is calculated by subtracting from the total DF the DFs for the other individual variances. I.e.:]

$DF_E = DF - DF_R - DF_C$

$= 11 - 3 - 2$

$= 6$

Computation of mean squares:

The mean squares are found by dividing in each case the sum of squares by the degrees of freedom (DF_x).

Row Mean Square (RMS) = RSS / DF_R

= 10,778.79 / 3

= 3592.93

Column Mean Square (CMS) = CSS / DF_C

= 957.20 / 2

= 478.60

Error Mean Square (EMS) = ESS / DF_E

= 82.96 / 6

= 13.83

3.3.3 Results and conclusions

[To calculate the test value *F*, we divide the relevant mean square (row or column) by the error mean square. This is shown in the ANOVA table below.]

ANOVA Table

Source of variation	Degrees of freedom	Sum of Squares	Mean Square	F
Rows	3	10,778.76	3592.92	RMS/EMS=259.79
Columns	2	957.20	478.60	CMS/EMS=34.60
Error	6	82.96	13.83	
Total:	**11**	**11,818.92**		

To determine whether the *column* effect is significant, we take our column *F*-value of 34.60. We compare this with the critical value for *F* at the 0.05 level, with 2 and 6 degrees of freedom respectively, in a statistical table, which is 5.14 (see, for example, Table IX in Hoel, 1976, pp. 338-341).

Our *F* value for the CMS/EMS variance ratio (also called the Main Effect for Drug) far exceeds this value; we can therefore reject the null hypothesis that the antihistamines do not significantly change visual performance.

[Note that there are always two values for degrees of freedom to be taken into account when comparing an *F* value with the values in a table: one for the numerator in the *F* ratio (i.e., the RMS if one is looking up the row main effect) and one for the denominator (always the EMS).]

The Main Effect for Subject is even more significant, as suggested by the plot.

3.4 Design precautions which should have been taken

(1) The order in which the drugs/placebo were administered to each subject should have been randomised. Despite the small number of subjects, this would go some way towards reducing the possibility of the *latent effect*[5] of one of the drugs potentiating the effect of another.

(2) Sufficient time should have been allowed to elapse between the administration of each drug to avoid any possibility of a *carry-over effect*[6] (i.e., the effect of the first drug treatment not having worn off before the second was given).

3.5 Two potential benefits from a repeated measures design

(1) Administering each drug more than once to each subject would have increased the reliability of the readings. For example, if each subject had been run twice for each drug, once in the morning and once in the evening, it would have been possible to control for time-of-day effects.

(2) Repeated administration of each drug to each subject would also have meant that it was possible randomly to vary the position of each drug for each subject in successive experiments. For example, if Meclastine was the first drug to be administered to Subject 1 in the first experiment, then it could have been administered second or third in a second experiment. This randomisation of the order of administration between experiments and within subjects would have provided an even stronger control for any latent effect than simply randomising the order of administration between subjects in one experiment as recommended in Section 3.4(1) above.

[5] See Appendix 1
[6] See Appendix 1

Appendix 1

Repeated measures and interaction effects

Repeated Measures

- **Definition:**

  Any experiment in which the same variable is measured more than once for each subject is a repeated measures design; e.g., a paired *t*-test in which two measures, 'before' and 'after', are taken for each subject S.

- **Advantage of repeated measures designs:**

  - they reduce overall variability by using fewer subjects

  - they control for individual differences

- **Disadvantages:**

  - the *carry-over effect* (e.g., effect of first drug treatment has not worn off before second is given and tested)

  - the *latent effect* (second drug potentiates or activates the latent effect of the first)

  - the *learning effect* (self-explanatory; most relevant to psychology experiments)

Interaction

An *interaction effect* should be thought of in contradistinction to a *main effect.*

- **Main Effects**

  A *main effect* is what we would measure if we were to collapse all our data into the several levels of a single factor and compare the resulting means.

- **Interaction Effects**

  An *interaction effect* can be thought of as a correlation or interaction between two or more factors. In other words, the influence of two or more factors is not independent of each other: they interact.

- **Interaction Effects may be 'second-order' but they are not necessarily secondary in importance**

  An interaction effect may be of greater interest than a main effect. In fact it may be the main object of investigation of an experiment.

See Howell (1997) for discussions of the basic ideas of both interaction (pp. 409-411) and repeated measures (pp. 450-452).

Reference:

Howell, David C. (1997). *Statistical Methods for Psychology* (4th edition). London: Duxbury Press.

Appendix 2

How to recognise what type of test to do

Type of measure	Nature of data	Examples	Suitable tests
Nominal	Discontinuous/categorical, having no regard for order	Gender Eye-colour	Non-parametric Chi-square
Ordinal	Discontinuous, but rank ordered	Social class Extraversion	Non-parametric, e.g., Chi-square. Parametric if plenty of ranks and normally distributed data
Interval	Truly quantitative and continuous, so intervals all equal; but zero point arbitrary	Fahrenheit Centigrade	Parametric
Ratio	Truly quantitative and continuous; intervals equal, and zero point not arbitrary, so, for example, a doubling of the measure obtained implies a doubling of the underlying quantity measured	Kelvin Age Weight Height	Parametric

Appendix 3

The theoretical distinctionbetween samples and populations

Its importance: '*Statistical methods may be described as methods for drawing conclusions about populations by means of samples'* Hoel, 1976, p.2

	Samples		**Populations**
Nature of measures:	Always empirical *(a posteriori)*		May be theoretical *(a priori)* (e.g., mean IQ score, or predictions from binomial); or, if unknown, may have to be represented by a sample.
Represented by:	English alphabet		Mainly Greek alphabet
Examples:	$\bar{x}$	Mean	μ
	s^2	Variance	σ^2
	S	Standard deviation	σ
	$\hat{p}$	Proportion	p

SAMPLING - Key concepts

Sampling error[7]

- the variability from sample to sample due to chance

Sampling distribution of a statistic

- 'the most basic concept underlying all statistical tests' (Howell, 1997, p.90)

[7] N.B., does not imply any mistake.

- tells us ‘what degree of sample-to-sample variability we can expect by chance as a function of sampling error’ (Ibid.)

- or ‘the distribution of values obtained for that statistic over repeated sampling’ (Ibid.)

- derived mathematically rather than empirically

Sampling distribution for the mean

- ‘distribution of means of an infinite number of random samples’ (Howell, 1997, p.90)

Standard Error

- the standard deviation of a sampling distribution of a statistic

General Bibliography

Textbooks of the kind listed below are usually updated every few years. If the reader finds there is an edition later than the one listed here, he or she is recommended to buy the latest version.

Greene, Judith and D'Oliveira, Manuela (1982). *Learning to Use Statistical Tests in Psychology*. Milton Keynes: Open University Press.

Hays, William L. (1994). *Statistics* (5th edition). Orlando, Florida: Harcourt Brace.

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Spiegel, Murray R. (1992). *Schaum's Outline of Theory and Problems of Statistics* (2nd edition). New York: McGraw-Hill.

Tabachnick, Barbara G. and Fidell, Linda S. (1983). *Using Multivariate Statistics*. London: Pearson Education Ltd.

Charles McCreery is a Research Director at Oxford Forum, an independent association of academics, set up to research and publish in currently neglected areas of psychology, theoretical physics, philosophy and economics.

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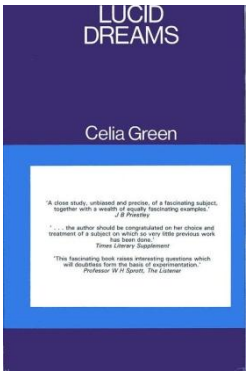
Lucid Dreams

Foreword by Professor H.H. Price, FBA



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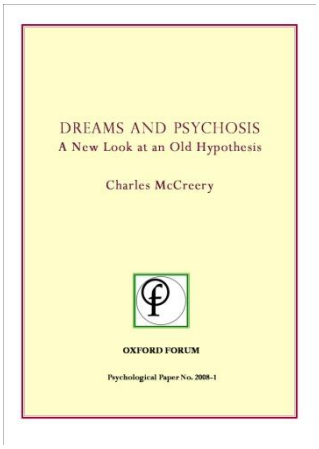

This paper proposes a theory of psychosis based on a link between sleep and hyperarousal. It is argued that the phenomenological similarities between psychosis and dreams arise from the fact that sleep can occur, not only in states of deafferentation and low arousal, but also in states of hyperarousal resulting from extreme stress.

It is proposed that both schizophrenic and manic-depressive patients are people who are prone to episodes of hyperarousal. Various sorts of electrophysiological evidence are adduced for this proposition, drawn from the fields of electroencephalography, studies of the galvanic skin response and studies of smooth pursuit eye movements. In addition, it is suggested that a key finding is the apparently paradoxical one that catatonic patients can be aroused from their seeming stupor by the administration of sedatives rather than stimulants.

It is proposed that a tendency to hyperarousal leaves certain individuals vulnerable to 'micro-sleeps' in everyday life, with the attendant phenomena of hallucination and other sorts of reality-distortion. Delusional thinking may follow as an attempt to rationalise these intrusions of dream-phenomena into daylight hours.

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Price £4.95; 34 pages
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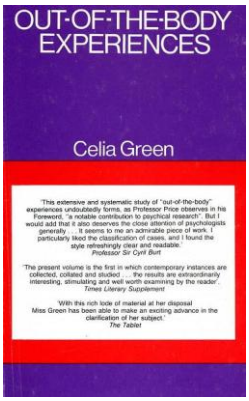
Celia Green

Out-of-the-Body Experiences
Foreword by Professor H.H. Price, FBA



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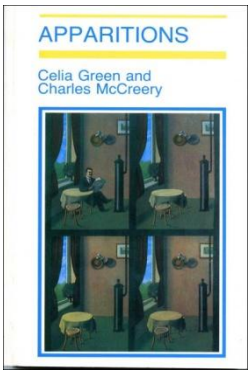

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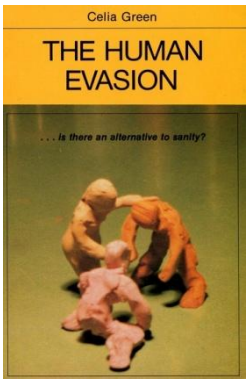

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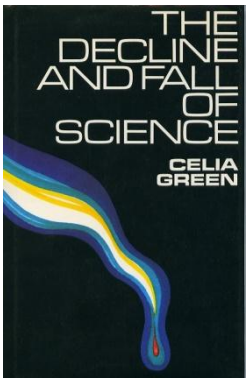

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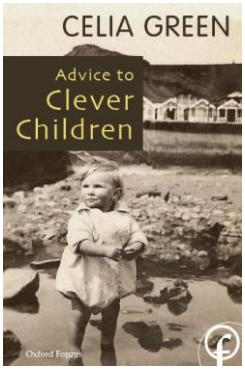

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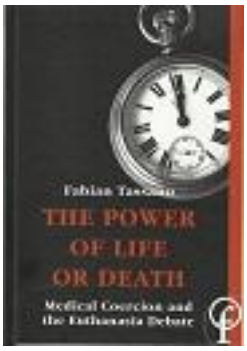

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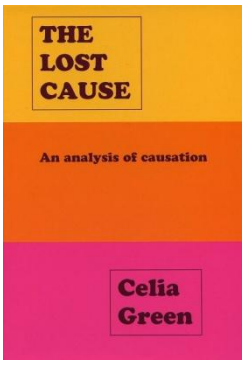
The Lost Cause
Causation and the Mind-Body Problem

Foreword by Professor Howard Robinson



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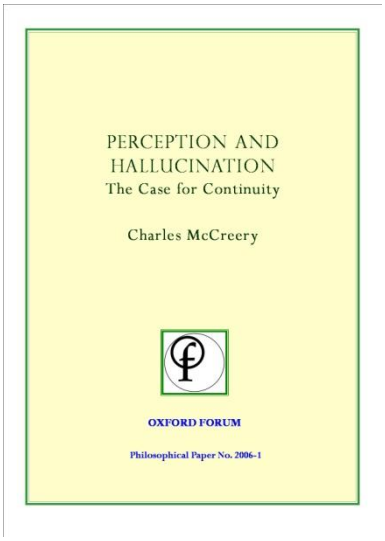

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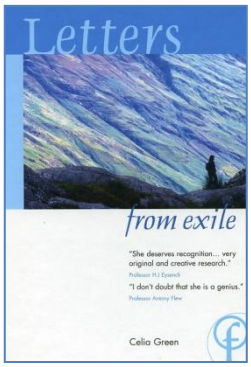

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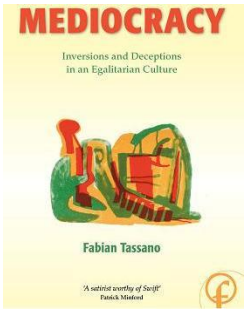

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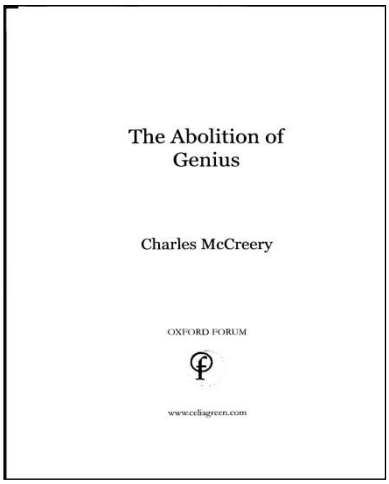
Foreword by Professor H.J. Eysenck, PhD, DSc



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