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STATISTICAL THINKING FOR NOVICE RESEARCHERS IN THE BIOLOGICAL SCIENCES

Postgraduate students from non-statistical disciplines often have trouble designing their first experiment, survey or observational study, particularly if their supervisor does not have a statistical background. Such students often present their results to a statistical consultant hoping that a suitable analysis will rescue a poorly designed study. Unfortunately, it is often too late by that stage. A statistical consultant is best able to help a student who has some grasp of statistics. It is appropriate to use the Web to deliver training when required and that is the mechanism used in this project to encourage postgraduate students to develop statistical thinking in their research. Statistical Thinking is taught in terms of the PPDSA cycle and students are encouraged to use other Web resources and books to expand their knowledge of statistical concepts and techniques.

1. INTRODUCTION

Much current statistical education of researchers is focused on training in specific techniques such as how to use statistical packages and interpret results. Not enough attention is devoted to such strategic issues as what technique is most appropriate and how to organise data collection. This paper describes a project that aims to fill this gap and to provide training in strategic research skills from a statistical viewpoint.

For instance, Day (1998) has tackled the problem of guiding young researchers through the research process. We wish to focus here on the statistical thinking required in the research process. This is not something that can be tacked on at the end but is intertwined with the contextual thinking throughout the whole project.

We have adopted the notion that statistical thinking takes account of variation and uncertainty, that it uses models for reasoning and that it brings together statistical understanding and contextual knowledge.

The inspiration for this project came from a paper by Pfannkuch and Wild (1998) and later, Wild and Pfannkuch (1999) who, following earlier work by MacKay and Oldford (1994), propose a cyclic model to describe the major elements of a statistical investigation, based on Problem-Plan-Data-Analysis-Conclusions (PPDAC). The model is cyclic because, at each stage, one must look forward as well as backward and the conclusions relating to one problem lead on to a new problem.

They propose zooming in at each stage of the cycle to gain more details of the stage at deeper and deeper levels. It is their view that statistical thinking occurs at the interface between statistical activity and context matter knowledge. They suggest that if the cyclic model targets a particular subject area, more expertise for synthesising the context knowledge and statistical knowledge can be incorporated into the deeper levels.

With a slight change of terminology, we have used this approach in this project. We prefer to name the cyclic elements, Problem-Plan-Do-Study-Act. The act of zooming in to gain more and more insight into a particular stage is particularly suitable for use on the World Wide Web. To that end we have sought in-depth information about each stage of the cycle and concentrated on the biological sciences for context matter as the application area.

Other authors have used the cyclic approach. Box, Hunter and Hunter (1978) give an excellent example of an investigation into water filtration that highlights using the conclusions of one experiment to form the next problem. We have taken the liberty of including several cycles from their example. Connolly (1996) has devised a research methods course for young researchers in the biological sciences. He considers the four phases of biological research to be Planning, Execution, Analysis and Reporting with various aspects of statistical thinking required in all stages. He illustrates the connections between the phases by using examples of defective experimental designs and emphasising the reasons to apply statistical methods and when.

Many authors have analysed and described what statisticians do and these can assist with deep descriptions of each stage of the cycle. Chatfield (1995) devotes much of his attention to the analysis (study) stage, and stress the importance of analysing data from properly planned studies. He distinguishes five main stages of a typical analysis, namely, look at the data, formulate a sensible model, fit the model to the data, check the fit of the model and utilise the model to present conclusions. Coleman and Montgomery (1993) provide a detailed method for planning an industrial experiment. Some of their details, such as the discussion of response variables and the tutorial on interactions, translate readily to the biological sciences.

There are a variety of papers discussing the concepts of statistics and statistical thinking. Bartholomew (1995) defines Statistics as being "concerned with the real world through the information that we derive from classification and measurement. Its distinctive characteristic is that it deals with variability and uncertainty which is everywhere." Pfannkuch and Wild (1999) summarise statistical thinking as taking account of variation, constructing and reasoning from models, transnumeration, and the synthesis of problem context and statistical understanding.

Gal (1998) distinguishes two contexts for interpretative skills, namely reporting and listening or reading. The novice researcher must be able to interpret, create, communicate and defend opinions based on statistical argument. Both contexts are relevant for researchers but data producers, at whom this project is aimed, are particularly concerned with the reporting context. Therefore, they must be able to defend the use of an experimental or survey design or the implications of an analysis of experimental data. On a similar theme, Moore (1998) argues that statistical thinking should be considered as a liberal art and that we should therefore spend more time on broad ideas rather than technical content.

There are many Web-based materials available for teaching introductory statistics course. Puranen (1998) and Ganesh & Ganesalingam (1998) discuss some of these. Many of these materials are aimed at first-year undergraduates. However, there are some designed for more advanced users. Talbot et al (1998) have developed an infrastructure, SMART, for publishing training materials in advanced statistical methodologies. SMART is aimed at established researchers in the biological sciences and, thus, it assumes that the researcher understands the research process and the place of statistics in the same. It became clear during the development of SMART that novice researchers would need more than an introduction to some of the modern methods of statistical analysis. They would need to be introduced to the statistical design process. To some extent, this has been addressed by including a checklist, and a link has been provided in the Statistical Thinking facility to this checklist.

Bishop (1998) tackled the issue from another angle by developing Web-based material for illustrating the basic concepts and terminology of experimental design. Two real experiments are used as illustrations with photographs and video clips while the student is able to experiment interactively with techniques such as randomisation and blocking. These experiments are a useful introduction to design and are based on lectures given to Statistics majors but do not include the whole statistical process. This introduction to experimental design has been linked to the statistical thinking facility.

The self access project at the University of Adelaide is developing schemes for enhancing undergraduate and postgraduate students' development as independent lifelong learners by means of an integrated series of Web-available learning resources in a number of different learning contexts. This will demonstrate to students a model of independent, resource-based learning on demand, involving self-access to a linked series of Lotus Notes databases in six main content areas with a common user interface and front page arrangement. The Statistical Thinking facility forms part of this project.

2. AVAILABLE STATISTICAL HELP

At the time that this project was instigated, there were several sources of statistical help provided by the Department of Statistics to University of Adelaide students. Undergraduate Science students were encouraged to take Statistical Practice I, a first year subject, equivalent to a one-quarter load for one semester. This subject used the textbook by Moore and McCabe (1999, and earlier versions). A second year subject, Statistical Practice II, following on from the first year subject was seldom taken by Science students, mainly because of timetable and funding problems. Some departments, such as Zoology and Geology, offered applied statistics subjects to their own students. It was possible for a postgraduate student who lacked statistical knowledge to audit undergraduate subjects. At the time of writing, all of these subjects are still offered.

However, other avenues of help are no longer available. The Department of Statistics offered a fee-paying course to the general public. This was a 72-hour course spread over 12 weeks and postgraduate students were encouraged to attend with the fee subsidised by the University. This was an introduction to statistical practice and not a course in research design. Postgraduate students were also entitled to five free hours of a statistical consultant's time. The five hours were usually divided between discussing the project with the consultant and the consultant performing some analyses; formal reports were not written. More than 100 students per year used this service.

One of the authors (Bishop) participated in this consulting service and observed that many postgraduate students who came to consult lacked sufficient statistical knowledge to have a meaningful discussion about the role of Statistics in their projects. Students were requested to write 200-500 words summarising their project before they came. Those that did usually gained a lot from the consultation. Bishop perceived that many of those who did not write the summary needed basic statistical explanations before the discussion could begin. It was departmental policy that the statistical consulting service should not become a dumping ground for data collected by students who had no idea how to analyse them.

Another area of concern was that many students collected data without any consideration of the statistical validity of the experimental or survey design. It would be a good idea to build on a student's basic statistical knowledge by demonstrating the many facets of statistical thinking. A book was not required, rather a succinct summary readily accessible when needed. Therefore, the Statistical Thinking facility was developed for the University of Adelaide Intranet.

3. DESCRIPTION OF THE STATISTICAL THINKING FACILITY

3.1. GENERAL OVERVIEW

The first screen of Statistical Thinking gives the user information about the purpose of the facility, the focus on biological sciences and how the first-time user should begin. There are ten headings or main topics:

- Introduction;
- Problem;
- Plan your experiment;
- Plan your survey;
- Plan your observational study;
- Do;
- Study;
- Act;
- Help with extra reading;
- Useful web sites.

One can see that the five steps of a statistical investigation are covered, with Plan having three options, depending on the type of data collection planned, i.e. experiment, survey or observational study. The first-time user is advised to begin with the Introduction, which explains the cycle with examples and gives instruction on using the facility. Other topics provide help with extra resources, either web-based or printed materials. The user can choose to expand all or some of the topic headings. This gives the next level of information and by choosing one of the subtopics, the user will open a screen of information about that subtopic. For instance, the topic, *Plan your experiment*, has the following subtopics:

- State the objectives for this experiment;
- Turn an objective into a hypothesis;
- Choose the response variables carefully;
- Select the treatments;
- Select the experimental units;
- Choose blocking variables;
- Plan collection of new data;
- Time plan;
- Plan analysis;
- Piloting and adjustment;
- Checklist.

The topics, *Plan your Survey* and *Plan your Observational Study*, have not yet been developed but they appear in Statistical Thinking as an indication of their usefulness.

3.2. DETAILS OF PLAN YOUR EXPERIMENT

We have identified these components as the necessary steps in planning an experiment. The most difficult step to write in a general sense was *Turn an objective into a hypothesis*. At the next level of detail it is as follows:

- *Remember that your experiment is conducted on a sample of experimental units so that you can infer the properties of the population* (usually called parameters) from which the experimental units were drawn. Any hypothesis relates to the population and its parameters.
- *Break your objective down into components*.
  - *You may want to know whether the mean response differs among the levels of a factor*. You can extend this to each of the other factors. For instance, you may want to know whether the mean wheat yield differs between fertiliser types, A and B.
  - *You may be interested in how two factors interact*. For example, are the responses to rates of application different between A and B? Alternatively, do the differences among wheat variety means depend on the application rate of fertiliser?
  - *Continue adding a factor until all factors are included*. For example, you may want to know whether the wheat varieties respond differently to fertiliser type and application rate.
- *Form a null hypothesis*, for example that the differences of interest do not exist in the population. The analysis of the data you collect will test whether the observed differences in means are strong enough evidence to reject the null hypothesis.

The user selecting *Choose the response variables carefully*, will open a screen with the following information:

Choose the Response Variables Carefully

A good response variable:

- *Is easy to record.* Imagine weighing a live pig.
- *Encapsulates the maximum possible information on the outcome of the investigation.* Continuous variables usually provide more information than binary or ordinal variables. Care should be taken that it is possible to analyse the data using the chosen form of the response variable. For instance, it is difficult to count large numbers of lesions on a leaf but is also difficult to obtain a meaningful result if the counting system in Table 1 is used.

Table 1. Example of Counting System

Number	Variable value
0	0
1 or 2	1
3-10	2
>10	3

- *Can be measured objectively on a generally accepted scale.* If a characteristic of interest is directly measurable, then that characteristic can be a response variable, e.g. plot yield or weight gain of an animal are directly measurable. Some characteristics are not directly measurable, e.g. size of an insect, intelligence, prompt service. Therefore, variables that represent that characteristic must be measured instead.

- *Is measured in appropriate units.* Units may be absolute, such as kilograms, degrees Centigrade or days, or they may be relative such as percentage mortality.
- *Takes values that discriminate well.* For instance, it is difficult to distinguish between mortality rates of 99.5% and 99.8%. It is hard to detect and distinguish contamination levels near zero.
- *Preferably has constant variance over the range of experimentation.* It will be much easier to analyse such a variable using standard statistical methods.

The above subtopic was collated from several sources, particularly Chatfield (1995) and Wild and Pfannkuch (1999).

3.3. SCIENTIFIC METHOD AND ROLE OF STATISTICS

The Introduction contains the subtopics:

- The Scientific Method;
- The Role of Statistics;
- The Five Stages of an Investigation.

The Scientific Method

Although there are potentially many 'scientific methods' in modern science, there is only one generally accepted approach to the solving of problems or the answering of questions. It is based around:

a. *Observation*: classification and measurement
b. *Laws*: accepted generalisations
c. *Theories:* working hypotheses
d. *Experimentation:* testing hypotheses
e. *Inference*: drawing conclusions and making predictions

Statistics has an important role to play in a, d and e.

The Role of Statistics

Statistics is the science of collecting, organising and interpreting numerical facts called data. To think statistically means that one can:

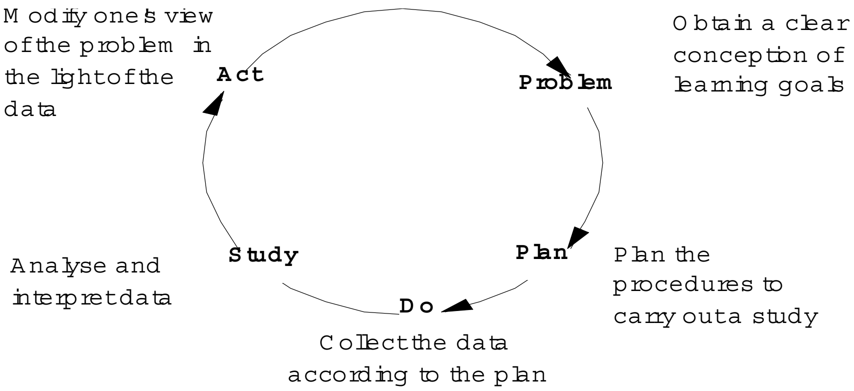
1. Read data, critically and with comprehension;
2. Produce data that provide clear answers to important questions;
3. Draw trustworthy conclusions based on data.

Statistics play a role in the:

1. Planning of surveys and experiments;
2. Collection and presentation of the data;
3. Analysis and interpretation of the data.

The Five Stages of an Investigation contains a diagram of the general PPDSA cycle, shown in Figure 1, and an example showing how the cycle is used in a specific experiment. Navigation through Statistical Thinking can be sequential where the user starts at some point, usually the beginning, and after reading a screen, clicks on the forward arrow. In addition, a back arrow follows the sequence in reverse. A user wishing to have more control can click on the up-arrow to return to the main topic list and then choose another topic or sub-topic.

Figure 1. The Five Stages of An Investigation



3.4. USEFUL WEBSITES

In some subtopics, useful web site addresses have been given and the user can link directly to them from within Statistical Thinking. For instance, the subtopic, *Adopt an Experimental Design*, discusses determination of number of replicates and contains a link to power analysis freeware available on the Web. A complete list of these web sites is also given as a separate topic. They are shown below.

1. For help with writing you thesis, *Writing and Presenting Your Thesis or Dissertation (http://www.canr.msu.edu/aee/dissthes/guide.htm),* provides many helpful hints on thinking about an appropriate topic, preparing the proposal, writing the thesis and defending the thesis (if your university requires a defence). There is a list of associated bookmarks, some of which will be useful in countries other then the USA.
2. An *Introduction to Experimental Design* is accessible via http://www.maths.adelaide.edu.au/people/gbishop/smart/mintroed/edframe.htm. It contains a brief explanation of the difference between observational studies and experiments, terminology used in experimental design, examples of real experiments and descriptions of how to carry out some experimental design procedures.
3. For an introduction to surveys, there are several documents available from the American Statistical Association. Start with *What is a Survey? (http://www.stat.ncsu.edu/info/srms/survwhat.html),* and follow links to documents about planning a survey, collecting survey data and privacy in surveys.
4. A comprehensive list of software for performing *power calculations* is available at (*http://sustain.forestry.ubc.ca/cacb/power)*. Some is freeware and can be downloaded, some can be used interactively on the web. There is general-purpose software that can be used for power analysis. Some software is dedicated to performing power analyses and some calculate sample size or probabilities but not power. Quite a few have been reviewed and links are provided to the reviews.
5. One site described at the power calculation site, performs *on-line randomisation* and is at: *http://www.stat.ucla.edu/calculators/powercalc*.
6. A *checklist* for making sure that you have covered everything in your experimental plan. (*http://www.bioss.sari.ac.uk/tele/strat/stratdesexp.htm)*

7. The US Environmental Protection Agency is a rich source of documents for carrying out scientific investigations of environmental issues such as air and water pollution. These documents show the rigour required in setting up the study and the role of Statistics in the overall plan. Start with *Guidance for the Data Quality Objectives Process* (http://es.epa.gov/ncerqa/qa/qad-docs/epaqag4.pdf). This process has been updated and applied to a specific type of investigation in *Data Quality Objectives Process for Hazardous Waste Site Investigations* (http://es.epa.gov/ncerqa/qa/qad-docs/g4hw-final.pdf). In particular page 72 of this document shows the iterative nature of the process in a similar manner to the PPDSA cycle.

4. EVALUATION

The first draft of the Statistical Thinking facility was available on the University of Adelaide Intranet at the end of August 1999. However, it was not publicised widely until February 2000. At that stage, postgraduate students who were prepared to use the facility and answer a questionnaire were offered a free statistical consultation. This was thought to be sufficient encouragement as the University's free statistical consulting service had been discontinued to all but Agricultural Science students several months beforehand. Free consultations were offered for a three-week period in February 2000. Twelve students applied for the consultation but some were beyond the deadline imposed by external constraints and so only six received the free consultation. The analysis of these students' responses was qualitative.

The six people who attended for a consultation all offered further comments to their original questionnaire responses. One student's responses were very negative, partly because he had had a lot of trouble accessing the Intranet. Most of his criticisms were directed at the Intranet screen layout, something over which I (Bishop) have no control. I was able to explain the way it worked during the consultation. However, he had not really worked through any of the material in Statistical Thinking, possibly because of his frustration. He wanted to know how many animals he should look at. Unfortunately, there were no published data to give any idea of variation among the animals of interest for the trait under study.

Two other students had not worked through the material either. One was at a very early stage of his thesis and needed help determining what variables to measure. The other could state his overall problem quite well but was unable to progress to describing the population about which inferences were to be made or to defining treatments. Both were engineering students and may have been put off by terms such as block and plot. One requested a downloadable pdf file of all the material and this was later included in the facility.

Two consultees had already completed their theses and both commented that they would have liked the facility at an earlier stage because their supervisors were unable to offer much help with Statistics. Both had problems with more advanced analysis, one requiring a mixed effects model and the other an examination of multicollinearity.

The sixth student was a Mathematics student with a background in biochemistry. He had been studying as much Statistics as he could and so found this facility more of a refresher than an introduction but did state that it had improved his ability to think statistically. He wanted more information on curve fitting.

Generally, the results from this qualitative study were disappointing. There were several contributing factors. The students who responded were desperate to receive the free consultation. They perceived their problems as specific to their own projects rather than ones that could be addressed by more general information. Statistical Thinking does not address the concerns of the last three consultees described above and one of them specifically requested that the facility be expanded to include various aspects of curve-fitting. This will be discussed later. The author (Bishop) offering the free consultation was about to leave the University of Adelaide and because time was short, found it difficult to insist on more thorough use of Statistical Thinking before the free consultation would be offered. Students were requested to bring a completed checklist when they came for a consultation but none complied. The third problem was the short time frame over which the evaluation took place.

These comments should be viewed in the context of a generally warm response to the facility from postgraduate co-ordinators within the University, a geology lecturer who taught geostatistics, the postgraduate students association and the university's educational advisory centre, who all helped to publicise the facility.

Usage of the facility was logged from August 29 1999 to April 17 2000. During this period, 69 users accessed the Statistical Thinking facility. The amount of time spent on the facility by each user is shown in Table 2.

Table 2. Number of Users Accessing Statistical Thinking for Each of the Time Periods.

Minutes of access	Number of users
0	6
1-5	27
6-10	16
11-15	4
16-20	4
21-25	3
26-30	1
31-35	3
36-40	2
41-45	1
46-50	1
51-55	0
56-60	1

Those who spent zero minutes merely hit the title page and left. Some people spent much longer on each screen than others. For instance, one user made 106 screen changes in 4 minutes 13 seconds and another made 169 screen changes in 21 minutes 53 seconds. At the other end of the spectrum, one user made only eight screen changes in 8 minutes 23 seconds. While there is a large number of short-time users, some of these are repeat users. The mean time spent accessing the facility was 10.08 minutes and the standard deviation was 12.87 minutes.

Most users started with the subtopics of the *Introduction* topic and worked through the facility in sequential order. Some previous users started where they had left off previously. Jumps out of sequence were usually to the *Useful Web sites* topic. Most users worked through part of, or the entire *Plan your Experiment* topic.

5. IMPLICATIONS FOR AND RELATIONSHIP TO THE TRAINING OF RESEARCHERS

A number of issues have arisen during the course of this project. Some relate to the specifics of the Statistical Thinking facility while others are more general.

Postgraduate students from non-statistical disciplines often have trouble designing their first experiment, survey or observational study, particularly if their supervisor does not have a statistical background either. Such students often present their results to a statistical consultant hoping that a suitable analysis will rescue a poorly designed study. Unfortunately, it is often too late by that stage. One aim of this project is that postgraduate students who use the facility when embarking on a research degree will be made aware of the need for statistical principles in the planning of their projects. Others have used different approaches to the same aim. For instance, Svenson (2001) emphasises the need for communication between the statistician and researcher, while Glencross and Mji (2001) use an integrated approach to research design and statistical analysis in their training courses.

The large number of hits made to the site, which is only accessible by staff and students within the University of Adelaide, indicates that postgraduate students and a few staff are keen to have statistical help. This is supported by co-operation received from various bodies within the University and by the audience response to talks about statistical help given at postgraduate student orientation days over the past few years. It should be noted that use of this facility has not been restricted to biological science students but is open to postgraduate students from all disciplines.

If one can generalise from experience with six students, students prefer to have advice directed at their particular problems rather than to read material that is more general. However, 69 people have accessed Statistical Thinking and the six who received a free consultation may not be typical of the others.

Harraway et al. (2001) have found that a variety of statistical techniques are used in just five branches of biological sciences. Rather than include a large number of analytical methods in this facility, it would be more fruitful to include links to descriptions of analytical methods that are available on the Web. There is a need for brief descriptions of methods that are not usually taught in basic Statistics courses. Talbot et al (1998) have addressed this need in part but more methods with examples are required.

A substantial proportion of users accessed the topics *Design your Survey* and *Design your Observational Study*, even though they were listed as under development, indicating that there is a need for these topics to be developed.

One indication that students are thinking statistically about their own projects is their ability to complete the checklist. the one linked to Statistical Thinking is long and involved and covers practically every aspect of designed experiments, surveys and observational studies. The reluctance shown by the trial group to complete this could be because it is just too difficult and perhaps a simpler checklist would be better initially. The longer one could be tackled when the student feels happier about some of the basic points.

Some students, once they have worked through the checklist, will be able to proceed directly with the experiment. Other students will be in a better position to reap the benefits of a consultation with a statistician because they will have a clearer plan for their experiment and a better idea of the questions to ask the consultant. One of the case studies in Harraway et al. (2001) indicates a student preference to be taught about study design to help formulate the questions to ask a statistician.

The other major issue that arises from this project is that of using Internet or Intranet facilities. Stangl (2001) lists four interrelated reasons that increase the chance of success of the Internet as a teaching tool over other technologies such as video and CD-ROM. One of these is interactivity and she points out its drawbacks of complexity and expense in developing and delivering the materials and of human factors such as time and the feeling of information overload. Both of these drawbacks were highlighted in this project.

One way that people accessing the Web overcome the problem of information overload is to download printable material and think about it later. Statistical Thinking is essentially text-based and so a pdf file with topics and subtopics in a table of contents has been provided. However, in using the text in this way, students lose some of the structure that aims to give overviews at different levels of complexity.

Some students who followed the link to the Introduction to Experimental Design link encountered problems with the interactivity provided by Java applets, video clip examples and photographic examples. Many students' computing resources do not support the first two of these and are very slow at downloading photographs. As Stangl (*ibid*) says, student access is the biggest hurdle. Furthermore, the inclusion of interactive applets, video clips and examples that rely on colour make printing for later reference difficult, if not impossible.

Harraway et al. (2001) refer to three basic approaches that postgraduate students may use to learn Statistics. They are attending formal lecture courses, attending specialist short courses and informally through their own reading. I would add a fourth approach to this list. The fourth approach would use the basic framework provided by Statistical Thinking, downloadable as a pdf file, much shorter than a book, easily updated and with structure that enable the student to follow a topic to finer detail when required. The facility would be rich in links to other web sites that illustrate poor design and its consequences, sites with examples of good design, sites that describe measurement methods, and sites that outline analytical methods with examples of appropriate use.

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