Advanced Higher Biology Project investigations

A guide for students and their teachers

Jim Stafford

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Foreword

Having taught first-year biology at university for many years, I find it easy to differentiate entrants who have Advanced Highers. They are more self-assured and are comfortable with taking responsibility for their own learning - which is the touchstone of a university education.

They have also gained the valuable experience of the Advanced Higher Investigation (or Project, as it will soon be known):

- gaining an insight into the process of research in the experimental sciences;
- the intellectual challenge of constructing a hypothesis, and experimental protocol to test it;
- the elation, when a data set is generated that is consistent with the hypothesis;
- the initial despair, if the data set in not consistent with it - and the realisation that this is 'OK' in the process of experimental science; often the more valuable result;
- the tedium of repeating some experiments, for whatever reason;
- the hard graft and challenges associated with constructing the Report;
- the final satisfaction with its completion.

Most of the statements above describe 'emotions' that surround the work. When I talk to university entrants about their AH Investigation, 'anxiety' is the overarching theme.

This Guide, from SSERC, fills a much-needed gap for both student and teacher. It provides generic guidance and support for both. It will be invaluable in detuning the anxiety of the Project, and enhancing the student experience and attainment.

Professor Iain Hunter
Executive Dean of Science
University of Strathclyde

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Preface

TO THE STUDENT

This booklet is designed to help you plan and carry out an investigation for the Advanced Higher Biology Project. A report of your investigation is required by SQA as assessment evidence for the Advanced Higher Biology Project. Although the booklet deals with writing up your report, the definitive advice on how to do this for course assessment is the SQA Instructions for Candidates. Both this booklet and the SQA Instructions for Candidates should be read in conjunction with each other throughout your project.

The introduction contains a flow chart to guide you through the process of investigation including quality assurance checkpoints at various stages. Each section of the booklet is set out in the same way: it starts with a summary of key points based on content entries in the syllabus, and the detail that follows explains what the entries mean and how they relate to assessment.

All of the information in the booklet is designed to cover the knowledge and skills you will require for the Unit assessment in *Investigative Biology* and for the course examination where there will be questions on experimental design and data analysis.

Although the investigation for the Advanced Higher Biology Project is your own work, it is important that you discuss your work and collaborate with others in developing ideas; that is how science is done, it is not a solitary activity.

Carrying out an investigation that you have devised and planned for yourself can be one of the most satisfying and rewarding aspects of science.
Good Luck!

TO THE TEACHER

This booklet is designed for teachers/lecturers to use with students who are embarking on an investigation for the Advanced Higher Biology Project. It is relevant to the Investigation of Advanced Higher Biology, Revised Advanced Higher Biology and to the Project of *CfE* Advanced Higher Biology. The philosophy behind the booklet and the SQA Project Guidance is that students should be supported in developing their skills of investigation. Students should not be abandoned to their fate, nor should they have their investigation done for them. This can be a fine line to tread. In the early stages of investigation, students are likely to need advice and support in choosing a suitable topic for investigation and in selecting an appropriate experimental design. As the investigation progresses, students should be making more independent decisions in the analysis and evaluation of their results. By referring to the advice in the booklet and in the SQA Instructions for Candidates, teachers can use open questions to assist students to reflect on and review their own work rather than provide excessive direction or support.

The booklet also attempts to cover the theoretical aspects of the Advanced Higher Unit *Investigative Biology*. Thus as well as supporting candidates in their investigation, it should prepare them for Unit and Course assessment. The underlying aim is that it should improve attainment, not only in the investigation for the Advanced Higher Project but also in the Course examination question paper and Unit assessment items that assess experimental design and data analysis.

Contents

Introduction

The Advanced Higher Biology Project investigation gives you the opportunity to carry out your own piece of scientific research.

You will learn how to meet and overcome the challenges of carrying out scientific practical work by:

- coming up with a suitable biology topic or idea on which to base your investigation
- researching the background biology of your investigation using a variety of sources
- developing questions or hypotheses to investigate
- devising suitable experiments to meet the aim of your investigation
- carrying out experiments and/or field work methodically, safely and ethically
- collecting data and making observations carefully and accurately
- reflecting on your results and devising further experiments
- analysing and presenting your results
- evaluating and discussing your experimental procedures and results
- writing a scientific report on your investigation.

The Flow Chart on the following pages summarises the whole process of investigation and provides quality assurance check-points as questions for you to think about at each stage. Use the Flow Chart to give you a quick overview of the whole process and as a reminder of what you should be thinking about at each stage. Then use the sections in the rest of the booklet to give you a fuller explanation of the things to consider. Each section starts with a summary of the key points to help you decide what is relevant to you for further reading. Not all of the detail in each section will apply to your particular investigation, so use it selectively.

The Course Examination question paper and the Unit Assessment can test any aspect of the Investigative Biology Unit so you will need to be familiar with all aspects of the booklet to prepare for assessment.

If you keep the Flow Chart by your side and refer to the rest of the booklet and the SQA Instructions for Candidates when appropriate along with any other resources you may have, you should be on the right track for a successful investigation.

"Imagination should give wings to our thoughts but we should always need decisive experimental proof, and when the moment comes to draw conclusions and to interpret the gathered observations, imagination must be checked and documented by the factual results of the experiment."

Louis Pasteur 1822 - 1895

FLOW CHART ON PLANNING AN INVESTIGATION

Some of the boxes in the flow chart have a quality assurance (QA) statement to help you reflect on what you may need to think about at that stage.

Preliminary stages

Choose an area of biology that you find interesting.
Talk about it to your fellow students and teacher/lecturer.

↓

Read about your chosen area. Make notes of ideas and experimental methods.
QA *Have you kept a record of the sources you used?*

↓

Decide provisionally on an aim for your investigation and devise questions that could be investigated through experiments or field work.

↓

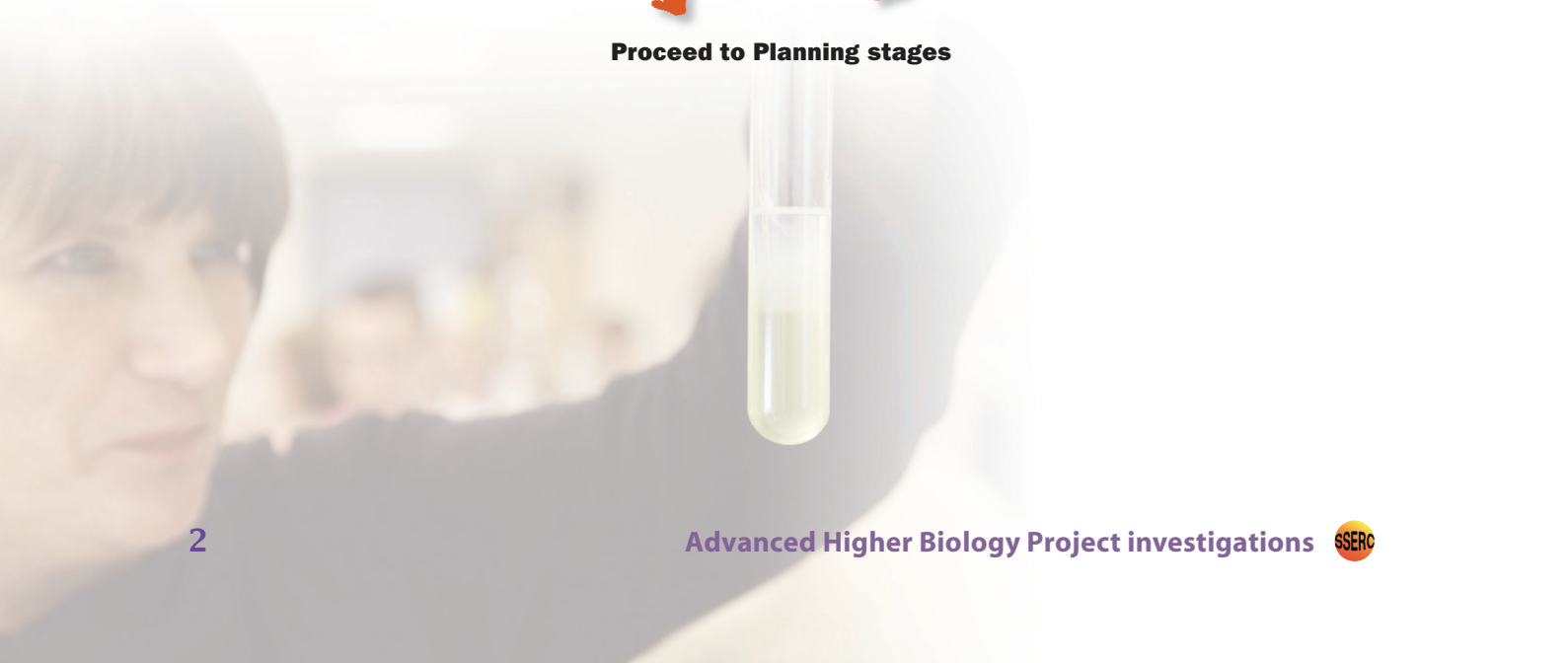
Make preliminary observations, experiments or a pilot study.
QA *Check 'turn around' times, seasonality and availability of resources and materials.*

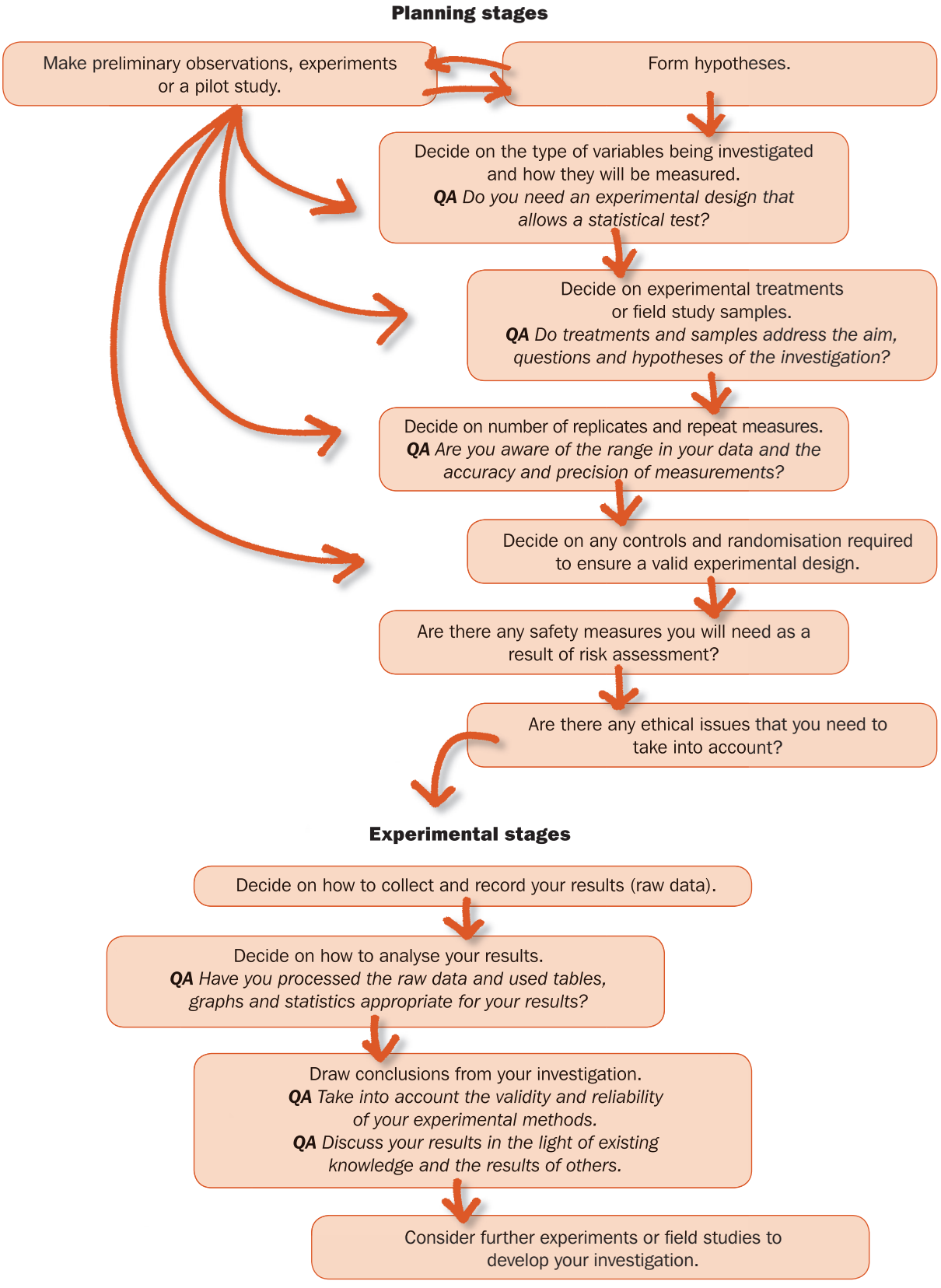
↕

Form hypotheses.
QA *Do the hypotheses address the aim and questions to be investigated?*
QA *Do you need to make use of a null hypothesis?*

↓

Proceed to Planning stages




Planning stages
Make preliminary observations, experiments or a pilot study.
Form hypotheses.
Decide on the type of variables being investigated and how they will be measured.
QA Do you need an experimental design that allows a statistical test?
Decide on experimental treatments or field study samples.
QA Do treatments and samples address the aim, questions and hypotheses of the investigation?
Decide on number of replicates and repeat measures.
QA Are you aware of the range in your data and the accuracy and precision of measurements?
Decide on any controls and randomisation required to ensure a valid experimental design.
Are there any safety measures you will need as a result of risk assessment?
Are there any ethical issues that you need to take into account?
Experimental stages
Decide on how to collect and record your results (raw data).
Decide on how to analyse your results.
QA Have you processed the raw data and used tables, graphs and statistics appropriate for your results?
Draw conclusions from your investigation.
QA Take into account the validity and reliability of your experimental methods.
QA Discuss your results in the light of existing knowledge and the results of others.
Consider further experiments or field studies to develop your investigation.

Getting Started

1

1.1 RECORD KEEPING

Key points

- *Good record keeping is vital for writing up your investigation report.*
- *Have an organised method for recording your work and date your work.*
- *Keep a record of:*
  - *all your early thoughts*
  - *discussions with your teacher/lecturer*
  - *all the references you consult*
  - *your experimental and fieldwork methods*
  - *all the raw data you collect.*

It is vital to keep a record of your work as you go along as you will depend on this when you come to write your final report. You will need to refer to your record of work when you discuss progress with your teacher/lecturer and they may wish to look at it when they assess your progress for Unit assessment.

All the work you do is important and should be recorded. There is always a temptation to dispose of, or delete, early work or initial versions as you progress. Do not do this; these early versions are a useful way to follow how your thoughts have developed when you come to write your final report. Nor should you think that only results are important, you will have to write an introduction and a discussion in your report where you may want to refer back to your early thinking and how your initial ideas changed as you progressed.

You will have to be organised about your record keeping. There are a number of ways to do this. Some will prefer the traditional hard backed laboratory notebook; there is a lot to be said for this. Some prefer to use a 'page to a day' diary to record their work. Others prefer to keep electronic files in a folder - if you do, then maintain a separate back up copy! Or of course you can use a combination of these as suits you best.

Whatever you use it is important to date your work. Often in biology, experimental results are collected after a period of days and the discipline of dating your work provides a double check of time intervals. Dating your work also helps you to put your thoughts in sequence at the writing up stage.

In your record of work you should do the following:

- Record all your early thoughts. You do not need to write lengthy continuous prose to do so; use bulleted lists, brainstorm lists, mind maps, spider diagrams, flow charts, keywords and single sentences that encapsulate an idea, thought or question as suits you best. Above all, keep these dated and organised. A good way to do this is read them over and then give your notes a title; for example 'ideas for a hypothesis', 'variables that could be investigated', 'techniques that could be used', 'useful references' etc, etc.

- Keep a record of your discussions with your teacher/lecturer and others dated as before. Again this does not need to be lengthy, it could be a record of decisions made, things to think about, questions to address, a 'to do' list etc, etc. You should make these notes as you go along, it is easier to do this than trying to recall everything afterwards!

- Keep a record of the text books, journals and websites you consult - you will need to include at least some of these as references in your investigation report, so this is a vital discipline. Keep these in the appropriate format, see the SQA Instructions for Candidates. It may help you to write a summary of the information relevant to your investigation from these references (an important scientific skill) - these could be useful when you write the introduction and/or discussion in your investigation report. Or you may want to make a note beside each reference as to its usefulness; for example comments like 'good overall summary', 'includes useful techniques', 'covers medical/economic/social significance', 'contrary point of view to other authors', 'supports my results', 'contains a useful diagram I might use' etc, etc.

- Keep a record of all your experimental and/or fieldwork methods. You will have to include these in your report written in such a way that another scientist could exactly replicate what you did.

- Keep all your *raw* results, including those that you think 'have not worked'. Unexpected results can be useful in the discussion phase of your investigation report or can be used as a starting point for refining a technique or method. All results are useful and relevant, there is no such thing as a bad result! The unexpected result may be an opportunity to provide an explanation for which assessment credit can be given. Keep a record of your processed results. You might process your results by carrying out calculations on your raw results (averages for example) or by presenting them in a table, graph or bar chart. Once you have processed your results it is a good idea to write down any conclusion that can be drawn from each set. A note you keep at this stage will help you when you come to write your investigation report. This is covered in more detail in Section 3 *Collecting, Anlaysing and Presenting Results*.

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1.2 CHOOSING A SUBJECT FOR INVESTIGATION

Key points

- *Read the SQA Instructions for Candidates and make sure your investigation will meet its requirements.*
- *Talk with others about your ideas for an investigation.*
- *Follow the 'Scientific Method' (see Theory Box 1).*
- *Develop your own idea for an investigation rather than be given one by someone else.*
- *Write down the aim of your investigation (see Theory Box 2).*
- *Keep your aim in mind but be adaptable and take account of your results as you go along to consider what to do next.*

Before thinking about the question you wish to investigate you should read the Instructions for Candidates produced by SQA for Advanced Higher Biology Project investigations. Your Teacher or Lecturer will probably give you a copy but you can get it for yourself on the SQA website (www.sqa.org.uk) in the Biology subject pages. The document lets you know what is expected of you in assessment terms; it is important that you make sure your investigation will enable you to meet these requirements. Your teacher/lecturer will be able to advise you on the necessary standards.

Although your investigation must be your own work it is not expected to be a solitary activity. You can and should discuss your plans and your ongoing work with your teacher/lecturer, laboratory technicians, fellow students and other teachers and scientists as appropriate. It is important to collaborate with others in developing ideas and to discuss methods - that is how science is done.

However although you are allowed to seek advice and support along the way, the decisions made, the practical work and the writing of the final report must all be your own work. Any advice and support should be acknowledged in your report; this recognition of the contribution of others is an important aspect of scientific work.

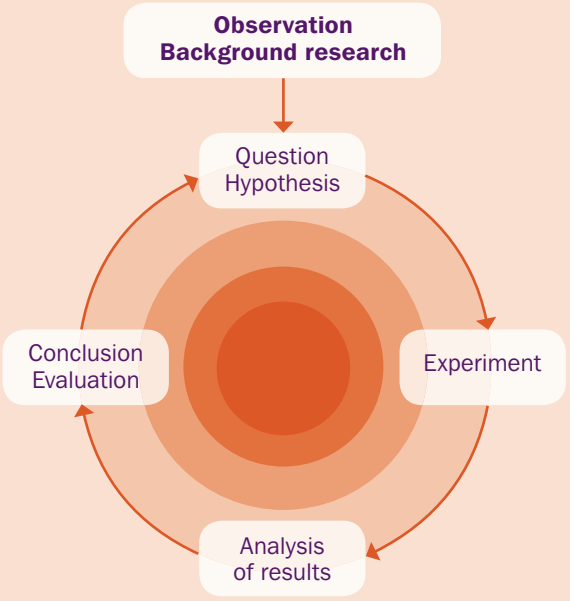
THEORY BOX 1

The Scientific Method

Scientific knowledge is constantly developing and changing. Current scientific knowledge can be considered as the best explanation available based on existing evidence. As new evidence comes to light scientific thinking changes and on occasion overturns long established scientific views. No explanation can ever be 100% certain as it is always possible some new evidence can be produced that supports an alternative explanation. We continually challenge our understanding with new experiments. Sometimes these experiments show that our understanding was incomplete or even partly wrong, and thus in need of revision. This potential for falsification and revision of scientific 'facts' is a key aspect of science and underpins the Scientific Method.

The Scientific Method is based on observation and planned data gathering by experiment or field work. As a result of observations (which may include reading about the observations or results of others) a question or hypothesis is formulated that can be tested. An experiment is set up or data gathered from field work and the results are recorded and analysed. The results and conclusion are then evaluated to confirm or refute (reject) the hypothesis. Once this is done a further hypothesis may be formulated and tested. This is the scientific cycle.

Scientific cycle



Failure to show an effect is a valid finding as long as the experiment is well designed. All results should be reported, even if they are unexpected. Conflicting data or conclusions can lead to explanations that can be tested by further hypotheses. One-off findings are treated with caution; conclusions only become accepted when evidence produced by other researchers supports them.

THEORY BOX 2

Aims, Questions and Hypotheses

How to write an aim

The aim is an explicit statement relating your variables to the organism, process or system that you are going to investigate. It may also include the method you will use to obtain results. Aims usually begin with the word 'To'. For example:

- To investigate the effect of salinity on the growth of brine shrimps
- To investigate the effect of lysozyme on bacteria
- To compare biological activity in a range of soils
- To compare plant biodiversity and abiotic factors on north and south facing aspects of a sand dune habitat
- To investigate the effects of ageing and denaturation on the structures and properties of fungal cellulase and other digestive enzymes using protein electrophoresis.

The aim can be adapted to come up with an appropriate and informative title for your investigation report. Once your investigation is near completion check that your original aim matches the work you have done and change it accordingly if it does not. Then by removing 'To investigate/compare etc' you may well have a suitable title for your investigation report.

Questions and hypotheses

A question is similar to a hypothesis but is more open ended in that a prediction may not be made. For example 'What effect will altering pH have on enzyme activity?' or 'What is the effect of detergent on the growth of pond algae?'

A hypothesis is tested by experiment or observation and often involves a prediction on how an independent variable will affect the dependent variable to be measured. For example 'As light intensity is increased, the rate of photosynthesis as measured by oxygen production, will increase' or 'As male deer increase in size they will have greater breeding success'. A hypothesis may also be written as a null hypothesis.

A *null hypothesis* proposes that there will be no effect from an experimental treatment. It is often paired with the *alternative hypothesis* that suggests there is an effect. The null hypothesis approach is useful where the raw data is to be processed with a statistical test. Statistical tests can only prove there is no effect; that is, they can show that any observed effects/differences between measurements can be explained by chance alone. If you can show that the results are very unlikely to be due to chance, then the null hypothesis is refuted and there is evidence for an effect, as suggested by the alternative hypothesis!

Above all you should bear two things in mind:

- It is best to choose your own project, one that you are interested in rather than one allocated by someone else. If it is your own idea, you are more likely to be motivated and stick with the project when the going gets tough, as it often does!

- Your investigation must not be a single experiment or a collection of unrelated experiments, but a linked series of experiments that together address the question you have set out to answer. Often as an investigation progresses your plans have to be adapted and altered in the light of experience. This is a good thing; it shows you can adapt your ideas in the light of your results and credit will be given for that in the assessment.

Once you have an aim for your investigation it will express in broad terms the question you are going to tackle. Write it down, keep a record of it and refer back to it as your investigation proceeds. It is easy to lose sight of the aim once you get into the nitty-gritty of the experimental work.

The next stage will be to design experiments that test a particular question or hypothesis (see Theory Box 2 and Section 2 *Designing Experiments*). It is important that these experiments are related to the aim of your investigation. If they are not, you will either have to think about other experiments that are better related to your aim or change your aim so that it relates better to your experiments. Both approaches are acceptable - this lateral thinking is often how science is done! However be wary of chopping and changing too much or your investigation may lose the continuous thread that should run through it, and time may also become an issue.

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1.3 STARTING POINTS FOR AN INVESTIGATION

Key points

You can base an investigation on:

- *an area of biology that interests you*
- *an experiment you have done before*
- *an experimental method you have found while reading or surfing web sites*
- *a piece of laboratory or field equipment*
- *a chance observation or passing thought.*

Thinking of a question to investigate is a serious challenge in its own right. "Eureka" moments where a brilliant idea enters someone's head are rare, but you can work towards such moments. There are a number of different starting points you can use to come up with an idea to investigate. These include:

- Think about areas of biology from previous courses that you have enjoyed or that have interested you. Go back and read about these areas again in your old notes and textbooks and then research them further by selecting key words to use in search engines and book indexes. Keep a note of the sources you find (you may need them later) and make notes from your reading to help you think about questions to investigate, or use techniques like brainstorming and mind mapping if you are comfortable with them. Look for experiments associated with these areas that you might be able to use. Discuss your thoughts, bouncing them around with your teacher/lecturer and others to help you develop your ideas. Be careful not to spend too long in this preliminary stage; it is important to start on the practical work as soon as possible.

- Think about biology experiments you have done in the past that you enjoyed or that interested you. Could they be adapted to form the basis of an investigation? Are there other variables that could be investigated using the same experimental set up or could the experiment be used with other species? Remember that an investigation must be more than one experiment, so this is a starting point from which a whole investigation could develop.

- You can also look for experiments that you have not done before but have been done by others. A search of experimental biology textbooks and/or websites (e.g. the Science & Plants for Schools (SAPS) www.saps.org.uk and Nuffield Practical Biology websites www.nuffieldfoundation.org/practical-biology) may well contain experimental protocols and procedures that catch your eye. These can be the starting point for developing an investigation. If taking this approach check that you will be able to obtain all the equipment and materials or any organisms you require, and that you are aware of any safety issues.

- You may be able to access a particular piece of laboratory or field equipment or apparatus around which you can build your investigation. Or you or a laboratory technician may be able to make a piece of equipment to use in the investigation. This is quite permissible and credit can be given for the development of the equipment, its calibration and mastering its use as part of the investigation as long as you write up this development phase in your report.

- Observation and curiosity can also be starting points for an investigation. You may have noticed something happen during class practical work and wondered what had caused it, or observed something during fieldwork and wondered what the explanation could be. Or you may have a question that crossed your mind while reading about science. These are early germs of ideas and often require more working up through discussion compared to the other approaches in this list. Nevertheless they can generate good investigations.

2 Designing Experiments

Key points
- *Have an aim for your investigation.*
- *Devise hypotheses or questions that you can address through laboratory experiments or field work.*
- *Think about using a null hypothesis or experimental designs that will allow for statistical tests of your results if appropriate.*

By now you should know (and have written down) the aim of your investigation. You should also have some questions and/or have formed hypotheses on which to base experiments or field work. You should also think about whether you want to use a null hypothesis (see Theory Box 2 - Aims, Questions and Hypotheses) or set up your experiments for a statistical test (see sub-section 3.3 Statistics in Section 3 *Collecting, Analysing and Presenting Data*).

2.1 HANDLING VARIABLES

Experimental variables

Key points
- *The variable you set or control is the independent variable.*
- *The variable you measure is the dependent variable.*
- *Other variables that might affect your results are confounding variables.*

The factors that affect your experiment or fieldwork are known as variables. As you design your experiment or field work you will have thought of the variable that you are going to alter or that alters naturally in the field; this is the independent variable. You will also have thought of the variable that you want to measure; this is the dependent variable. The measurements you make of the dependent variable will be your results. You will be trying to establish if changes in the independent variable have an effect on the measured values of the dependent variable. You will also have thought about other variables that might affect your results that you will need to keep under control; these are the confounding variables.

2.1.1 Types of variables

Key points
- *Quantitative variables are measured on a numerical scale (e.g. length, temperature, response time).*
- *Qualitative variables are measured in categories (e.g. red, white or pink flowers) by counting the number in each category.*
- *Ranked variables are measured in order of magnitude (e.g. from rare to abundant).*

Biological variables can be quantitative, qualitative or ranked. The type of variable being investigated has consequences for the data you collect and for any graphical display or statistical tests that you may use later.

Quantitative variables can be measured on numerical scale. They may take any value on a numerical scale, e.g. temperature or absorbance. Or they may only be measured by whole numbers, e.g. number of eggs in a clutch or heart beats per minute.

Qualitative variables are descriptive. The terms used are discrete categories, e.g. male/female, viable/non viable, shapes, colours. Data are recorded as direct readings or counts. Counts can be computed to produce frequencies, ratios or percentages.

Ranked variables can be listed in rank order, e.g. of magnitude (such as first, second, etc). Or descriptive terms can be allocated a numerical rank, e.g. a five point scale to describe the abundance of an organism (rare (1), occasional (2), frequent (3), common (4), abundant (5)) or to evaluation responses in a questionnaire (strongly disagree (1), disagree (2), neither agree or disagree (3), agree (4), strongly agree (5)).

Think carefully about the variables in your investigation and decide to which of the above categories they belong. Then decide how you are going to measure each variable. More detail on measuring variables is included in sub-section 2.6 *Measuring variables*.

2.1.2 Natural variation, sampling and replicates

Key points
- *A number of measurements must be taken to give a true value for a measured variable due to natural variation.*
- *In the laboratory replicate experimental treatments and in the field take a representative sample from a population to determine the natural variation in your measured values.*
- *Be careful not to measure one individual several times, this will give you the variation in measurement error not natural variation.*
- *Be careful that the categories for qualitative variables do not overlap.*
- *With ranked variables clearly define each rank and avoid having too many ranks (suggested maximum of five).*

Random variation is everywhere in biology. If you measure a variable in one individual you cannot assume that all other individuals will have the same measured value. To get round this in the laboratory you would replicate your experimental treatments and measure them. In fieldwork you would take a sample of individuals from the population that are likely to have the same range of measured values as exists in the whole population and measure them. The range in these measured results will give you an indication of the natural variation in your data. Based on this information you can decide on the number of replicates or the sample size you need to give you a true value for your measurement.

When working with quantitative variables you will have to think about what would be a suitable sample size or number of replicates to use. Be careful not to measure the one individual several times; this is not replication. Repeating the measurement of one individual gives a measure of the variation in the method of measurement (the measurement error) not the random variation between individuals. To decide on a suitable sample size or number of replicates you need to look at the variation in measurements between individuals. If the range of values for individual measurements is small then a small sample size or small number of replicates would probably suffice. If the range is large then you will need a bigger sample or more replicates.

When working with qualitative variables you will need to ensure that the categories are clear cut and that there are no 'grey areas' or overlap where an individual could belong to more than one category. In general the fewer categories the better, the more categories you have, the more room for error there is. Also, you will also need to ensure that all of your observations can be allocated to the categories you have devised; this is where a pilot study can be useful.

When working with ranked variables the aim is to get consistent results each time a measurement is made. In ranked variables the intervals between the scale points need not be the same, it is the order that is of interest. When using ranked scales (such as rare, occasional, frequent, common, abundant) it is best to use a five point scale rather than scales with more points as this leads to more consistent measurements between experimenters. Clear and readily understood definitions will need to be made about what is meant by each category - e.g. rare or frequent and so on.

More detail on sampling and replicating variables is included in sub-section 2.2 *Sampling from populations and sub-section* 2.7 *Ensuring reliable results* sections later.

2.1.3 Controlling confounding variables

Key points

- *Confounding variables are factors that may affect the dependent variable.*
- *Confounding variables should be held constant, or failing that measured so that you can take them into account.*
- *A randomised experimental design (see Theory Box 3) can limit the effect of confounding variables (including those that you might not be aware of).*

Due to the complexity of interactions found in biological systems, factors other than the independent variable may affect the dependent variable. These factors are confounding variables. You will need to identify these and where possible hold them constant. Failing that, measure how they change during the experiment so that you can take them into account in the analysis of your results. For example the temperature in the laboratory may vary; so you may wish to use a water bath or incubator held at a constant temperature or monitor the laboratory temperature for the duration of the experiment so that you can take any temperature changes into account.

It is not always possible to identify the confounding variables that might affect your experiment. You can get round this by using a randomised experimental design. To decide which individual gets which experimental treatment you can draw lots, use a random number generator or use random number tables. For experiments that involve several experimental treatments, you can set up a 'block' containing one of each of the treatments and then randomise the blocks. This randomised block design is particularly suited to field trial type experiments. Randomisation reduces the influence any confounding variable is likely to have by making it the same across all the experimental treatments.

THEORY BOX 3

Randomised Experimental Designs

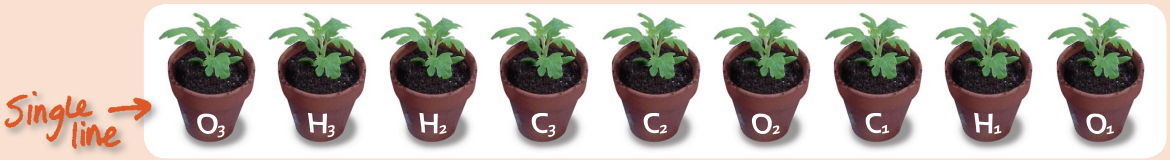
Randomised experimental designs are useful when there may be a confounding variable that cannot be readily controlled or easily measured. The principle of randomisation is to arrange the experimental treatments in such a way that the effects of any confounding variables are 'cancelled out' over the experimental design as a whole.

For example, a student wanted to investigate the effect of vitamin C on the formation of roots in plant cuttings. She decided on three treatments:

- dipping the cuttings in a vitamin C solution (the experimental treatment)
- no treatment (a negative control)
- dipping the cuttings in plant hormone rooting powder (a positive control)

She then decided to have three replicates for each treatment, giving a total of nine cuttings. She labelled the pots containing the cuttings C_1, C_2, C_3 (vitamin C treatments); O_1, O_2, O_3, (no treatments); and H_1, H_2, H_3 (hormone rooting powder treatments). She then intended to place the cuttings on a north facing window sill where they would get bright light but not direct sunlight that might dry out the cuttings. She was aware that the level of light may not be even along the window still so she decided on randomising the placement of her cuttings on the window sill. She considered three options of how to place her cuttings.

The first option was to put them in a single line along the window sill. The pots are numbered 1 to 9 and a random number generator is used to determine the order of the pots along the window sill. The result of such an arrangement is shown below.



The second option was to arrange the treatments in 'blocks' where each block contains one replicate of each treatment. The blocks are arranged so that any confounding variable is likely to be the same for each block and the treatments are arranged at random in the blocks as shown in the arrangement on the right.

The third option known as a 'Latin square' is similar to the random block design above except that the treatments appear once in each column and once in each row as shown on the left.

A further advantage of random block and Latin square designs is that they support certain types of statistical analysis such as an analysis of variance (ANOVA).

2.1.4 Experimental treatments and controls

Key points

- *The experimental treatments are the different conditions set for the independent variable.*
- *A control (treatment) is a reference against which experimental treatments are compared.*
- *When the control treatment is the absence of the experimental treatment this is a negative control.*
- *A positive control is a treatment that is designed to show the expected effect of an experimental treatment.*
- *A simple experiment has one experimental treatment, a multifactorial experiment has two or more experimental treatments in its design.*

Experimental treatments are the different conditions that are set for the independent variable in an experiment. Controls (control treatments) are used for comparison with treatment results to determine the extent of an effect. A negative control receives no treatment and, when compared to the experimental treatment, it shows minimal effect. A positive control demonstrates the effect predicted by the hypothesis and therefore the extent to which the experimental treatment compares. For example, in an experiment to investigate the activity of the enzyme catalase in a variety of tissues, the breakdown of hydrogen peroxide by catalase can be detected by testing for the presence of oxygen. Including a treatment without a sample of tissue would be a negative control and including a treatment with bought-in pure catalase would be a positive control. Experiments may have both negative and positive controls.

Simple experiments involve a single experimental treatment and a control. For example, when evaluating the effect of an "energy drink" on performance, participants might be split into a treatment group who each consume a fixed amount of the drink and a control group who consume nothing (a negative control). However, in some cases it may be more appropriate to have a different control. It might be more realistic and interesting to give the control group an equal volume of water to the "energy drink" group (a placebo), or allow the control group to consume whatever they would normally (a positive control). You should decide which comparison or comparisons (you can have more than one control group) would be most interesting to make. A placebo is an inactive substance used as a control in 'blind' experiments where you do not want participants to know whether they are receiving the experimental treatment or the control.

Multifactorial experiments take account the interaction of two or more experimental treatments. This is a useful design for looking at the combination of effects. For example the action of lipase on fats in milk can include the addition of bile salts as an additional treatment. Thus the experimental treatments would be: lipase alone, bile salts alone, lipase and bile salts, no lipase or bile salts. This is a four treatment (including a control treatment) multifactorial experiment. Multifactorial experimental designs allow a more complex range of questions to be addressed and can be used to investigate interactions that are likely to occur in real life. In this case we can ask the following questions:

- How does lipase affect fats in milk?
- How do bile salts affect fats in milk?
- Are the effects of bile salts and lipase on fats in milk independent, or is the effect of one influenced by the presence or absence of the other?

2.1.5 Observational studies

Key points

- *Observational studies do not have the independent variable and dependent variable design of an experiment.*
- *The values for two measured variables may show a correlation but this is not evidence of cause and effect. We do not know which variable influences the other or if there is another variable which influences them both.*
- *Observational studies are often followed up with an experimental study to investigate causation.*
- *Observational studies measure naturally occurring events rather than the manipulated events in a laboratory experiment.*

Sometimes it is not possible to have an experimental design with an independent variable that can be manipulated. Here instead we might record values for two variables and see if there is a relationship between them. If there is a relationship then it is correlation rather than cause and effect (causation) as we do not know which variable is affecting the other or indeed if it is a third variable that is affecting them both. Despite this apparent drawback such correlation studies are valuable when it is not practicable or in some cases not ethical to manipulate an independent variable. As observational studies measure naturally occurring events they are less likely to introduce any unintended experimental effects as a result of the manipulation of an independent variable.

An example of an observational study was the link between smoking and lung cancer investigated by recording the smoking habits (smokers and non-smokers) of British doctors and measuring their incidence of lung cancer. This famous study, carried out in the 1950s, showed a positive correlation between smoking and lung cancer. Although it did not prove a causative link between smoking and lung cancer it provided the justification to do other experimental studies that did demonstrate a causal relationship. In such observational studies it can be an advantage to compare a control group that does not show the outcome or result of interest. In this case that would be the smoking habits of doctors who did not develop lung cancer. Doctors were chosen for this correlation study as it was considered that the two groups (smokers and non-smokers) would be similar in many other respects relevant to lung cancer; so reducing the likelihood of confounding variables and that they would be reliable in recording data and sticking with the study to its completion.

2.2 SAMPLING FROM POPULATIONS

Key points

- *To be representative, samples should have the same mean and degree of variation as the population as a whole.*
- *Highly variable populations require a larger sample size to be representative.*
- *In random sampling, all members of the population have an equal chance of being selected for the sample.*
- *In systematic sampling, members of a population are sampled at pre-determined regular intervals.*
- *In stratified sampling, the population is divided into similar groups which are then sampled proportionally according to the size of the group.*

In some studies the experimenter may wish to use groups that already exist, so there is no truly independent variable. This is common in field studies and in some studies on human populations. These investigations are still valid and are good at determining correlation between variables from which conclusions can be inferred but they are less useful for determining cause and effect as the scientific method has not been directly tested. Nonetheless they can make for effective biological investigations.

A sample needs to be representative of the population as a whole. The sample should share the same mean and the same degree of variation around the mean as the whole population. The extent of the natural variation within a population determines the appropriate sample size. More variable populations require a larger sample size.

There are three types of sampling: random, systematic and stratified.

In random sampling, members of the population have an equal chance of being selected. For example in quadrat sampling of a field study area; the area is divided into quadrat squares, which are allocated a number. A random sample is then selected to be part of the study using a random number generator. The number of quadrats that form a representative sample can be determined by calculating a cumulative mean or cumulative total of the species of interest in the quadrats. Once you have a steady value, you are likely to have a representative sample size. When sampling individuals from a population or group each individual should be allocated a number and then use a random number generator to select the individuals for the sample.

In systematic sampling, members of a population are sampled at regular intervals. For example in field work, a line or belt transect could be placed in the area of interest and samples taken at regular intervals along the transect. In human population studies a school or class population could be sampled by selecting individuals at regular numerical intervals on a class list.

In stratified sampling, the population is divided into categories that are then sampled proportionally. For example, in the field, an area might have smaller areas (sub areas) with different characteristics. When the area is divided into quadrats and the quadrats counted, the proportion of quadrats in each sub area would determine the number of quadrats to be sampled from each area. In a human population study individuals could be grouped (stratified) according to age, gender etc and then randomly sampled for experimental treatments. For example, if we know that the population sex-ratio is 50:50, we can make sure that 50% of our sample is female and 50% male by drawing the first half of our samples only from females, and the second half only from males.

2.3 ETHICAL EXPERIMENTATION

Key points

- *Report your results honestly, do not be tempted to 'correct' or 'improve' your results.*
- *Acknowledge those people who help you and cite the work of others in references.*
- *Observe plants and animals in their natural surroundings wherever possible and keep the disturbance of natural habitats to a minimum.*
- *Maintain the highest care and welfare of animals at all times.*
- *Human subjects should be volunteers and give informed consent to participate. The results of human studies should be anonymous.*
- *Use and observe relevant Codes of Practice.*

Integrity and honesty are of key importance in science and these qualities should be reflected in your investigation.

Results should be reported honestly and accurately including any experimental variation and sources of error in the results. Marks are not awarded for getting 'the right result', indeed discussion of variation and potential sources of error are more likely to lead to insightful further experimentation and explanations for which marks can be awarded. In that sense honesty is certainly the best policy! At the same time do not be over critical of your own work; be proud and state your achievements clearly. Investigations with proper replicates and controls are more likely to show variation and sources of error and therefore lend themselves to honest reporting. Not only is this honest, but it is good science and as a consequence more likely to achieve high marks.

As well as honesty in reporting results it is also important to acknowledge the work of others and those who have given you advice and support. When summarising the background biology in your Introduction you should cite the references you draw from. A good way to distinguish what are your original thoughts and what you have copied from references is to use an on-line plagiarism checker. Where teachers, lecturers, technicians and other scientists have helped you with advice, equipment or resources you should acknowledge them in a list of acknowledgements in your investigation report.

When carrying out experiments you should also take ethical considerations into account if you are working with living things.

In field studies, natural habitats should be subjected to the minimum disturbance to achieve the aims of the investigation. Principles of conservation should be applied, animals and plants being observed in their natural habitat wherever possible rather than collected for observation. Where plants or animals are collected, avoid collecting unnecessary numbers, avoid collecting protected species and return plants and animals to their habitat as soon as possible.

In animal studies, the well-being of the animal is of prime importance. Animals should be well cared for with access to fresh water, a suitable diet and an environment suited to their needs including the opportunity to express their normal behaviour. The principles of replacement, reduction and refinement ('the three Rs') should be used to avoid, reduce or minimise stress in experimental animals. Stress can be minimised by using as few animals as possible to produce a meaningful result. However, care should be taken when using as few animals as possible that you do not apply too many treatments to the same limited number of individuals. Animals that are used to being regularly handled are less likely to be stressed in experimental situations.

When using human subjects in an investigation, the subjects should be informed of the nature of the investigation. Potential subjects should be invited to participate on a voluntary basis and should know that they have the right to withdraw at any point. The purpose of the study and its intended outcomes should be explained to the participants. Information should be provided on what participants will be expected to do and any resulting risks or potential benefits to them explained. This is the basis of informed consent. Results should be treated with confidentiality and made anonymous, e.g. by coding results rather than using names. Keep a copy of any information sheet or consent form you devise and include them in your investigation report as an appendix.

In any work with living things you should make it clear what measures you have taken to address these ethical issues. The SSERC publication *Materials of Living Origin - Educational Uses (2012)* is a useful source of advice and guidance in this area.

THEORY BOX 4

Scientific Ethics in the UK

Scientific work should always be justified in terms of its planned outcomes. The benefits of the outcomes of scientific research should be outlined (including the advancement of knowledge). Results should be reported honestly and accurately including any contrary findings and any conflicts of interest should be declared. Experimental variation and error should be reported and discussed with the results.

The UK science community has a strong record of taking a lead in ethical science. It has produced an ethical code for all scientists and established the ethical principles that underlie licensed research with animals, the three Rs - replacement, reduction and refinement. The UK led the development of the five freedoms of animal welfare for farmed and domestic animals. And the British Psychological Society has produced a Code of Ethics and Conduct based on the principles of respect, competence, responsibility and integrity for conducting experimental work involving human participants.

An Ethical Code for Scientists

- Act with skill and care, keep skills up to date.
- Prevent corrupt practice and declare conflicts of interest.
- Respect and acknowledge the work of other scientists.
- Ensure that research is justified and lawful.
- Minimise impacts on people, animals and the environment.
- Discuss issues science raises for society.
- Do not mislead; present evidence honestly.

The Three Rs that underpin the use of animals in scientific research

- Replace the use of animals with alternative techniques, or avoid the use of animals altogether.
- Reduce the number of animals used to a minimum, to obtain information from fewer animals or more information from the same number of animals.
- Refine the way experiments are carried out, to make sure animals suffer as little as possible. This includes better housing and improvements to procedures which minimise pain and suffering and/or improve animal welfare.

The Five Freedoms of Animal Welfare

1) Freedom from Hunger and Thirst - by ready access to fresh water and a diet to maintain full health and vigour.
2) Freedom from Discomfort - by providing an appropriate environment including shelter and a comfortable resting area.
3) Freedom from Pain, Injury or Disease - by prevention or rapid diagnosis and treatment.
4) Freedom to Express Normal Behaviour - by providing sufficient space, proper facilities and company of the animal's own kind.
5) Freedom from Fear and Distress - by ensuring conditions and treatment which avoid mental suffering.

As a result of these ethical approaches and also health and safety concerns, certain aspects of scientific research in the UK are regulated and licensed by Government. Legislation also limits the potential for the misuse of studies and of data. Ethical considerations can also influence the direction and pace of scientific progress through policy and funding decisions by government and charitable foundations.

2

2.4 SAFE PRACTICE

Key points

- *A hazard is something that can cause harm.*
- *A risk takes into account the likelihood of harm happening and the severity of that harm.*
- *Discuss risk assessment with your teacher and follow control measures or Codes of Practice to manage risk.*

The key to safe practice in carrying out laboratory or field work in biology is to understand the hazards and risks associated with the substances, biological agents and procedures you are working with and to put in place control measures that reduce the potential to cause harm. A hazard is the ability of a substance or biological agent to cause harm. Risk is the likelihood of harm occurring due to the method of exposure to any biological, chemical or physical hazards.

Although you may identify any hazards and consider what control measures are required to reduce risk to an acceptable level in your investigation, the legal responsibility to carry out a risk assessment remains with the school/college. That is why it is essential to discuss safety issues with your teacher/lecturer before embarking on laboratory experiments or field work so that all the necessary risk assessments are in place and you are aware of how to comply with them.

In some cases, as a result of assessing risk, following a standard code of practice such as the SSERC publication *Safety in Microbiology (2012)* can provide suitable and sufficient control measures.

2.5 PILOT STUDIES

Key points

- *A pilot study helps you to try out methods, come up with ideas, check timings and plan your investigation.*
- *See the bullet list below to see what might apply to a pilot study for your investigation.*

A pilot study is a small scale study of the biological system you intend to investigate. It gives you the opportunity to try out experimental methods to see if they are realistic and workable. It helps you to plan procedures and to check the validity and reliability of your experimental design. Remember any pilot study is part of your investigation and details of it should be recorded in your investigation report.

A pilot study can be used to:

- make observations that lead to identifying questions to investigate or hypotheses to test
- examine an experimental set up to decide on the appropriate measurements to take
- develop a new protocol
- evaluate different protocols to find the one best suited to the investigation
- practise using a protocol to become proficient
- identify the appropriate number of replicates for each experimental treatment
- identify the number of individuals required in a sample to make it representative of the population as a whole
- determine a suitable range of values for the independent variable to avoid results for the dependent variable that are 'off the scale'
- determine appropriate sample sizes so that counts made avoid 'floor and ceiling effects'
- determine the 'turn around time' for a protocol to see how it fits into the time available for the investigation
- establish the precision of measurements by making repeated measurements of an individual datum point
- establish the accuracy of measurements by calibrating instruments or checking against other measurement methods to find a true value
- help you think about how you will process and present your results (including the use of statistics if appropriate)
- help you develop a plan for the investigation as a whole.

As an example of floor and ceiling effects, imagine that we wanted to look at the performance of girls and boys in mathematics by giving samples of boys and girls the same test to complete. If the test is so difficult that no-one (girl or boy) can do it, then we have a *floor effect* where everyone scores zero and we don't really learn anything about the relative abilities of boys and girls. If we make the test too easy then everyone will get 100% and this *ceiling effect* means we again don't really learn anything about whether girls and boys are different. We instead want to design a test that is just challenging enough that we see a range in test scores in the boys and a range of test scores in girls. This variation gives us the best chance of picking up whether boys and girls differ on average.

As an example of measured values being "off the scale" imagine that you want to weigh individuals of different breeds of dog by standing on bathroom scales while holding the dog and subtracting your weight when you stand alone on the scales. If there

are breeds of dog such that your weight combined with the dog's weight is greater than the largest value your bathroom scales can report, then you have an "off the scale" problem - where you cannot work out the exact weight of the dog, only that it is greater than some value. When this happens you need to change your design to incorporate a different method of measurement.

2.6 MEASURING VARIABLES

Key points

- *When using a measuring instrument to record quantitative variables be careful to:*
  - *use an instrument that has the appropriate sensitivity (resolution) to measure the changes taking place in the variable*
  - *read scales accurately within the limits of measurement it is possible to make*
  - *avoid spurious accuracy by adding decimal points when changing units or calculating averages*
  - *be consistent in the use of units.*
- *A biological assay (bioassay) can be used to measure a quantitative variable indirectly by measuring the response of a plant, animal or microorganism to the variable rather than measuring the variable directly.*
- *When deciding on categories to record qualitative or ranked variables be careful to:*
  - *avoid categories that overlap*
  - *have a clear specification for each category*
  - *make sure the categories will give reliable, repeat results, e.g. with different observers or on different occasions with the same observer.*
- *Use methods such as tally counters and grids where appropriate to make counts of qualitative variables.*
- *When using time sampling to observe animal behaviour consider using measures such as the latency, frequency or duration.*

Once you have decided on the variables you are going to investigate, you will need to decide on how to measure the variables and what data to collect. This will require careful thought and preparation, and possibly research into the techniques others have used in similar studies to the one you have planned.

In the case of investigating a quantitative variable you will probably be using a device of some sort to make a measurement. Here the accurate reading of a scale will be important. Choose an instrument with a scale appropriate to your investigation; if changes are small you will need a device with a fine scale, if the changes are large a coarser scale may suffice.

The resolution of the measuring device, the smallest change that the device can detect in the quantity it is measuring, must be appropriate. Be careful to record your results within the limits of the measurement and do not introduce spurious accuracy by adding additional decimal points when changing units or calculating averages.

Be consistent in the units you use for your measurements. SI units are preferred but other units (such as minutes rather than seconds and litres rather than decimeters cubed) can be used if they are more appropriate to your study. Select a measuring device appropriate for the job, for example fine range pH paper might be more appropriate than universal indicator paper. Do your best to make sure measuring devices are properly calibrated (see sub-section 2.7 *Ensuring reliable results* below) so that results are accurate.

In some cases where a direct measurement of a biologically active substance is not possible a *biological assay* (bioassay) can be used. Here the response of a living plant, animal or microorganism is used to measure the presence of a biologically active agent by measuring the organism's response to it rather than measure the presence of the biological agent itself. In such cases the results will be comparative between different treatments rather than giving absolute values. For example, measuring zones of inhibition around wells, containing potential disinfectants, in a bacterial plate.

When measuring qualitative or ranked variables defining the categories of each variable is vital. Categories must not overlap and the categories should be clearly defined so that someone repeating the experiment will obtain the same result. The three potential sources of error in measuring qualitative variables in categories are:

- Overlap of categories. This is best addressed in a pilot study or trial experiment to ensure that the categories measure what is intended (validity) for the investigation planned.
- Inconsistent measurements. This can be avoided by a clear specification of what each category means (e.g. defining abundant as comprising more than 80% of the species present).
- Observer variability. This often occurs where there is a subjective element in making measurements. To reduce this you could either repeat your measurements or ask someone else to make the measurements, compare the two sets of results and then refine your methods accordingly. It can be useful to change or randomise the order of recording your results to highlight any order

effects in measurement. Where appreciable levels of subjective judgment are required, 'blind' procedures should be used wherever possible.

For example imagine that we wanted to explore whether people felt that full-sugar sodas tasted better than low-calorie alternatives. We might take the sodas out of their original bottle or can and present each to our experimental subjects in identical paper cups without telling the subjects which drinks are low-calorie and which are full sugar. This makes the subject *blind* to which treatment group (full sugar or low calorie) any particular drink belongs to when they give you their subjective score of how that drink tastes to them. This reduces the risk that their answers are biased by any preconceptions they may have about sugar versus artificial sweeteners in drinks.

When observing animal behaviour useful measures can be:

- latency - the time taken from the presentation of a stimulus to the first occurrence of a behaviour
- the frequency of a behaviour in a time period
- the duration of a behaviour.

Continuous observation of animals can be laborious and observing more than one animal at a time, impossible. This can be overcome by time sampling where the observation period is broken up into shorter intervals and the behaviour sampled at each interval. This approach is suitable for behaviour patterns that last for a relatively long period of time (states) but not for behaviours that are relatively instantaneous (events). Deciding on what to measure and whether time sampling or continuous sampling is appropriate is best determined from trial experiments or a pilot study. A pilot can be used to evaluate potential experimental designs to see if they meet the aims of the investigation (validity).

Research is critical when deciding upon how to measure variables and what data to collect. Use devices such as tally counters and grids when making counts to improve accuracy and reliability. For example, quadrat squares can be divided into a grid of smaller squares to make counts and a haemocytometer is a microscope slide with a known volume divided into a grid to make counts of microorganisms. It is particularly beneficial to gain from the experience of others by talking to your teacher/lecturer, other scientists and technicians and to consult specialist references on the techniques for making measurements in the particular biological field you are interested in.

2.7 ENSURING RELIABLE RESULTS

Key points

- *Have sufficient replicates or a sufficient sample size to ensure that random natural variation does not affect obtaining a true value for the measured variable.*
- *Make sure confounding variables are controlled or measured so that you can take their effect into account. Consider the use of a randomised experimental design to control unknown confounding variables.*
- *Use measures of central tendency, in which the range of values is compared to a middle value, to measure the random variation in replicates and samples.*
- *Use box plots to show the dispersion in a range of measured values.*
- *The variation in repeated measurements of an individual datum point gives an indication of measurement error.*
- *Precision is the closeness of repeated measurements to each other.*
- *Accuracy is the closeness of the measured value to the true value.*
- *Bias or systematic error is where the results may be precise but vary from the true value. Such results may show the trend of the true values even although there is a systematic error.*
- *Ensure the accuracy of results by calibrating equipment correctly or by checking the measured value using one or more other methods.*
- *Where personal operator bias is a possibility use 'blind' methods.*
- *Repeat experiments to determine the reliability of results.*

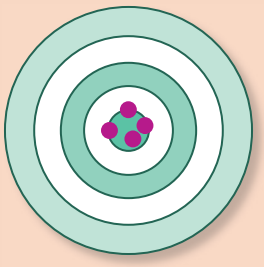
In addition to the experimental treatment effects, variation in experimental results may be due to the random, natural variation found in individual specimens and/or the precision and accuracy of the measurement methods. Using the methods in the key points above that are appropriate to your investigation is the key to a successful investigation and good marks. This can appear daunting at first; it can feel like you are pulling apart your own work! However it is this critical analysis that will serve you well when it comes to writing your report; it will give you the information to produce a high quality discussion that will gain credit at the high end of the marks scale. Be careful not to do your own work down; state clearly what your results show, draw your conclusions and then evaluate and comment on the reliability of your data.

Reducing the effect of random, natural variation to obtain more reliable results can be achieved as described in sub-sections 2.1.2 *Natural variation, sampling and replicates* and 2.1.3 *Controlling confounding variables* in Section 2.1 Handling variables. The extent of natural variation in a set of replicate treatments can be measured by its dispersion. This often involves comparing the range of measured values to a middle value. For a quantitative variable the appropriate middle value is usually the mean of the results. The results will form a range of values around the mean, some deviating from it on the higher side and some lower. A box plot of the range of measured values will show the dispersion of the data and is a good way to quickly assess the quality of your collected data. A standard deviation and/or standard error could be determined to give a measure of the variation in the data. A mean gives a more reliable measure of the true value than a single measure. For qualitative data the middle value is the mode, the most frequently occurring value. For ranked data the middle value is the median.

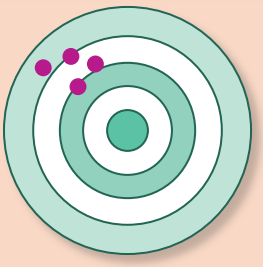
Measurement methods can also affect the reliability of the results. Precision is the closeness of repeated measurements to each other. You can investigate the precision of any measurement method by repeating measurements of a single reading (individual datum point) to show measurement error. Accuracy is the closeness of a measured value to the true value. Beware spurious accuracy in the presentation of results. Only include figures to the degree that the measuring instrument allows. Be careful to avoid changing the number of significant figures when changing units or carrying out calculations such as averages. Accuracy of measurement can be checked by using properly calibrated equipment, or by checking measurements using another, different measurement method. Results that are not accurate lead to bias or systematic error. If the bias or systematic error is consistent, then although not accurate, the results may still reflect the trends shown by the true values. Personal bias may also be introduced by an operator who has ideas about what the results should be. This can be avoided by using 'blind' measurements where the operator does not know the identity of the individual samples by, for example, using a coding system. In general precision is the more important practical consideration and will lead to accurate results unless there is bias in the system.

Finally overall results can only be considered reliable if they can be achieved consistently. Experiments should be repeated to determine the reliability of results.

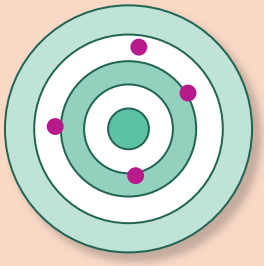
Target diagrams illustrating accuracy and precision



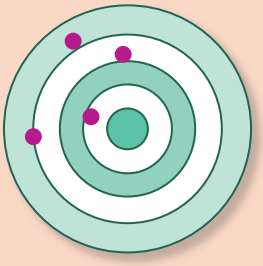
Accurate and precise



Precise but not accurate (shows bias or systematic error)



Accurate but not precise (shows range or random variation but mean is close to true value)



Neither accurate nor precise (shows random and systematic error)

3 Collecting, Analysing and Presenting Data

3.1 TABLES

Key points

- *Record your raw data by drawing up a table following the guidance in the bullet points below as appropriate for your experiment.*
- *Summarise the raw data in a table by for example:*
  - *calculating totals, rounding values, converting values to scientific notation as appropriate*
  - *calculating measures of central tendency such as the mean, mode or median as appropriate*
  - *considering calculating range, standard deviation, standard error or employing any statistical tests that are appropriate for your data.*
- *When presenting results in a table for your report:*
  - *The first column should normally be the independent variable.*
  - *For quantitative data the independent variable should be in ascending or descending order as suits your data best. For qualitative data the independent variable can be re-ordered to show patterns in the dependent variable if desired.*
  - *The second column should contain the measurements for the dependent variable.*
  - *Subsequent columns should contain any other dependent variables measured, replicates (although these can be included in an appendix if that would make the table clearer) or summarised results as appropriate such as totals, means, range, standard deviations, or values from statistical tests.*
  - *Include the variable and units (including scientific notation if used) in column headings; values in the table should be numbers only.*
  - *Give your table an appropriate title.*
- *When examining your tables of data look beyond the results you were expecting. Look across both columns and rows for patterns or trends that indicate any other findings. Write down what you notice, this will be useful when you come to write your report.*

In most cases the most convenient way to record collected raw data will be in a table although photographs and diagrams can be used where appropriate. Record the date and time when data were collected; also note details of the location and environmental conditions in the case of field work.

Tables to record raw data should be made up as indicated below, before collecting the data.

- The first column in the table should show the value (or category) of the independent variable. The subsequent columns should be used to record the values for each replicate or sample of the dependent variable.
- In time line studies the first column should show the chosen time intervals and subsequent columns the measured variable for each replicate, sample or treatment. If each treatment has replicates, the replicates should be grouped together as columns under each treatment. Alternatively each treatment could have a separate table to record results.
- If several variables are measured for the same organism or sample, each should be given a row.
- Include additional columns to allow processing the results, e.g. for totals and means, or to make annotations or comments.
- Make sure the boxes in the table are large enough to record your data.
- Make up multiple blank tables in advance as required.
- Above all organise your tables to reflect the order in which you will record your data (although you may wish to alter this later when presenting your results).

Now that you have your raw data the next stage is to process the data to simplify and summarise it so that patterns and trends in the data can be seen more readily. This may involve:

- calculating totals (from tally charts for example)
- rounding - no rounded values should include more significant figures than are in the measured data being processed)
- converting figures to scientific notation (a decimal number followed by a power of 10 e.g. 2.7×10^4).

When summarising the data in a table you may wish to provide a measure of central tendency of the data such as the mean (for quantitative data), the median (for ranked data) or the mode (for qualitative data). You may also wish to give the range for the replicates or samples measured. If the data show a normal distribution you may also wish to show the standard deviation. Measures such as the range and standard deviation describe the variation in your data. This will be useful later when you discuss your results as you can comment on the sources of variation that may have affected the quality of your data and on how representative the measures of central tendency are of the data.

Once you have summarised your data you should think about how to present your results to show any patterns, relationships or trends. Although tables can show patterns and trends it is also worthwhile looking at your results in the form of a graph to see if this gives a better indication of any trends. If you decide to present your results as a graph in your final report you should also include the table it is based on so that the examiner can check your data.

Image: Renjith Krishnan/FreeDigitalPhotos.net

Be careful when looking at your results. It is all too easy to look for what you want to find and then miss something unexpected. Try to look at your results with a fresh eye to see all the trends and patterns there are. In tables look across both columns and rows for effects and in graphs look at the shape and patterns and think about what that may mean. It is a good idea once you have done this to write down in words what you see in your data; imagine you are explaining the data to someone unfamiliar with your work. This will help you later when you come to discuss your results.

When using tables to present your final data, the same conventions should be followed as when collecting your raw data in tables. The first column should normally be the independent variable. For a quantitative variable the values may be in ascending or descending order as suits your data best. For qualitative data the independent variable can be re-ordered to show patterns in the dependent variable. Column headings should contain the variable name and units; values in the table should be pure numbers. Remember to round numbers or use scientific notation where appropriate. Where figures in scientific notation are all to the same power of 10, the power of 10 can be included in the table heading with the units leaving significant figures in the table. Tables should have a suitably descriptive title.

3.2 GRAPHS

Key points

- *In graphs the convention is that the independent variable is plotted on the X (horizontal) axis and the dependent variable on the Y (vertical) axis.*
- *Error bars are used to show the variation in the measured values around the mean for a treatment. If error bars overlap the differences between the treatment means may be due to random variation in the data or samples rather than a treatment effect.*
- *Line graphs are used for quantitative variables.*
- *Bar charts are used for qualitative variables.*
- *Box plots show the central tendency of collected data. Use box plots to show the range, dispersion and middle value (median) of collected data.*
- *Other more rarely used graphical forms include: pie charts, histograms, kite diagrams, logarithmic graphs and scatter diagrams.*
- *Graphs should have the axes labelled with the variable and units and have a suitable title. Scales should include all the data without excess empty space.*

Graphs are used to show the relationships in data. The three most commonly used ways of graphically analysing data in Advanced Higher Biology Investigations are line graphs, bar charts and box plots. Other forms of graphical presentation that may be used are described briefly below.

Error bars are used to show the variation in the measured values around the mean for a treatment. If error bars do not overlap then we can conclude that there is a treatment effect. If the error bars show the range or standard deviation in the values, then even if error bars overlap there may still be a treatment effect. However if error bars show the confidence intervals from a statistical test, then if the error bars overlap the differences between the treatment means are not *statistically significant* and cannot be attributed to a treatment effect.

3.2.1 Line graphs

Line graphs should be used for quantitative variables. The convention is that the independent variable is plotted on the X (horizontal) axis and the dependent variable on the Y (vertical) axis. The axes should be labelled with the variable and units. The scale on each axis should be selected to include all of the data without excess empty space on the graph. Scales need not necessarily start at zero. Where more than one data set (line) is plotted, they should be suitably labelled. Plotted points may be joined by lines or a line of best fit may be drawn. Lines of best fit should only be used where there is clear evidence, or it is known, that there is a mathematical relationship between the variables. Often in biology it is not certain (or known) that there is such a relationship or confounding variables or random variation may mask any mathematical relationship. Thus in the majority of cases it is safer to join the dots to show patterns or trends in the data. Error bars may be used at each plotted point to show the variation in replicates or repeated measurements. Line graphs should have a suitably descriptive title. Where more than one line is plotted on a graph, include a legend that details the symbols used to plot each line.

3.2.2 Bar charts

Bar charts should be used for qualitative and ranked variables. The convention is that the independent (qualitative) variable is plotted on the X (horizontal) axis and the dependent variable on the Y (vertical) axis. The bars may be lines or blocks of equal width, which do not touch. The bars can be in any order, but it can be helpful if they are arranged to show any pattern or trend (in ascending order for example). The axes should be labelled with the variable and units (if appropriate). The scale on each axis should be selected to include all of the data without excess empty space on the graph. Error bars may be used in the bars to show the variation in the samples. Bar charts should have a suitably descriptive title.

3.2.3 Box plots

Box plots (sometimes called box and whisker diagrams) are particularly useful for showing the variation in samples or replicates. They show the minimum, lower quartile, median, upper quartile and maximum values. They are good for showing the range, dispersion and central tendency of collected data. Different samples can be shown in much the same way as a bar chart with the different samples on the X (horizontal) axis and the numerical values on the Y (vertical) axis. Box plots should have a suitably descriptive title.

THEORY BOX 5

Presenting Data in Tables and Graphs

The purpose of presenting data in tables and graphs is to help display the meaning of your results, not just simply to record your data. Drawing tables and graphs summarises your data and allows analysis of your findings. The first thing to consider is whether you are presenting data from quantitative or qualitative variables or whether you wish to present the variation in raw data:

- quantitative data can be presented in tables and line graphs
- qualitative data can be presented in tables and bar charts
- variation in raw data can be presented as a box plot.

Quantitative data

For example in an experiment to determine the effect of the concentration of a sucrose solution on the mass of potato tissue, a student measured the mass of four replicates of potato tissue (the dependent variable) at four different sucrose concentrations (the independent variable). The results are shown in the table below.

Notice that:

- The table has an appropriate title.
- The independent variable (sucrose concentration) is the first column and is in ascending order (it could be descending order if that was appropriate).
- The first column heading describes the independent variable (concentration of sucrose) and gives the units of its measurement (mol dm^{-3}).
- The second to fifth columns give the measured values for the four replicates.
- The second column heading spans the four replicates, describes the dependent variable and gives its units.
- The remaining columns process the given data to give the range, mean and standard deviation of the data.

The effect of concentration of sucrose solution on the mass of potato tissue*

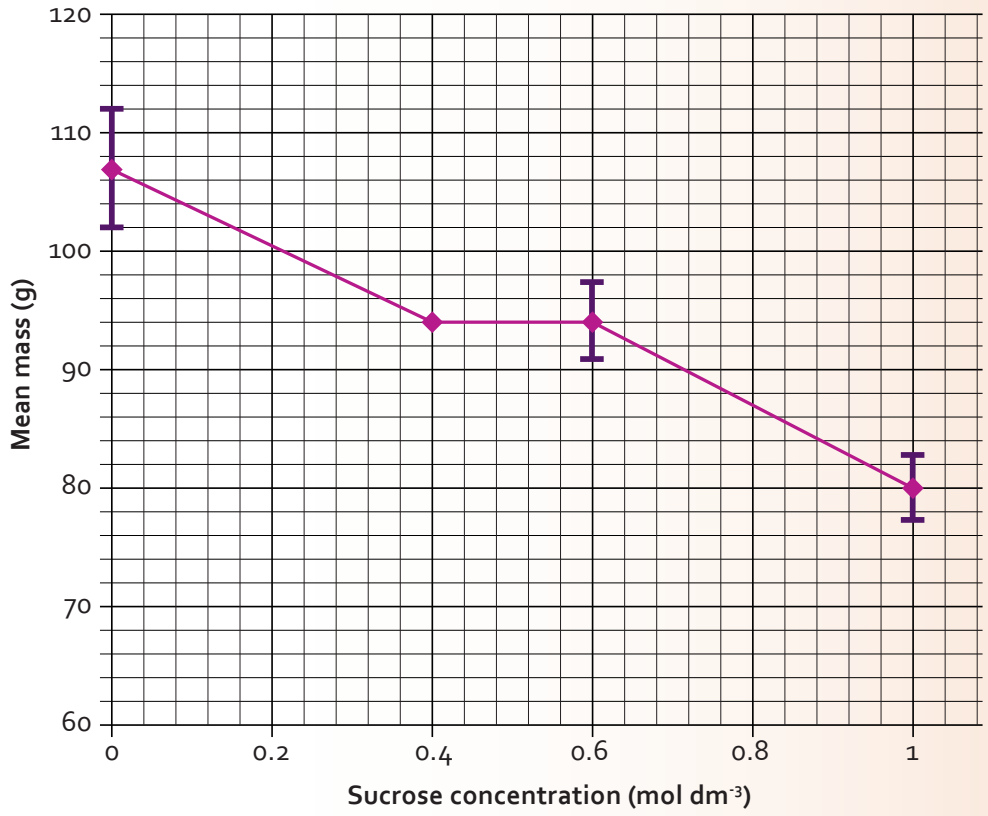
Concentration of sucrose solution (mol dm^{-3})	*Change in mass of samples 1 to 4 (% of initial mass)*				*Range*	*Mean*	*Standard deviation*
	1	**2**	**3**	**4**			
0.0	109.28	104.78	112.35	100.63	11.72	106.76	4.82
0.4	93.96	93.55	93.88	94.00	0.45	93.85	0.27
0.6	93.79	92.79	98.65	91.25	7.42	94.12	3.20
1.0	84.04	77.59	80.00	79.39	6.45	80.25	2.72

* Adapted from Biological Nomenclature, 4th Edition, Society of Biology, 2009.

THEORY BOX 5 - CONTINUED

The data is plotted in a line graph below.

The effect of concentration of sucrose solution on the mass of potato tissue



Notice that:

- The graph has an appropriate title.
- The dependent variable (mean mass) is plotted on the Y (vertical) axis.
- The independent variable (sucrose concentration) is plotted on the X (horizontal axis).
- The axes are labelled with the variables and their units.
- The scales for the axes have been selected to avoid excess empty space on the graph.
- The plotted points are joined by straight lines rather than a line of best fit.
- The standard deviation is shown as an error bar at each plotted point (at a concentration of 0.4 mol dm^{-3} the SD is too small to appear on the graph).
- As there is only one plotted line there is no need to have a key of symbols for different lines of plotted points.

THEORY BOX 5 - CONTINUED

Qualitative data

For example a student set up an experiment to investigate the loss of water from plant leaves by smearing the surface of leaves with a thin layer of Vaseline to prevent water loss. There were four experimental treatments (the independent variable): a leaf smeared with Vaseline on both surfaces, a leaf with Vaseline on the upper surface, a leaf with Vaseline on the lower surface and a leaf with no Vaseline. Five replicate leaves for each treatment were set up. The mass of the leaves was measured at the start of the experiment and again after four days. The results are shown in the table below.

Notice that:

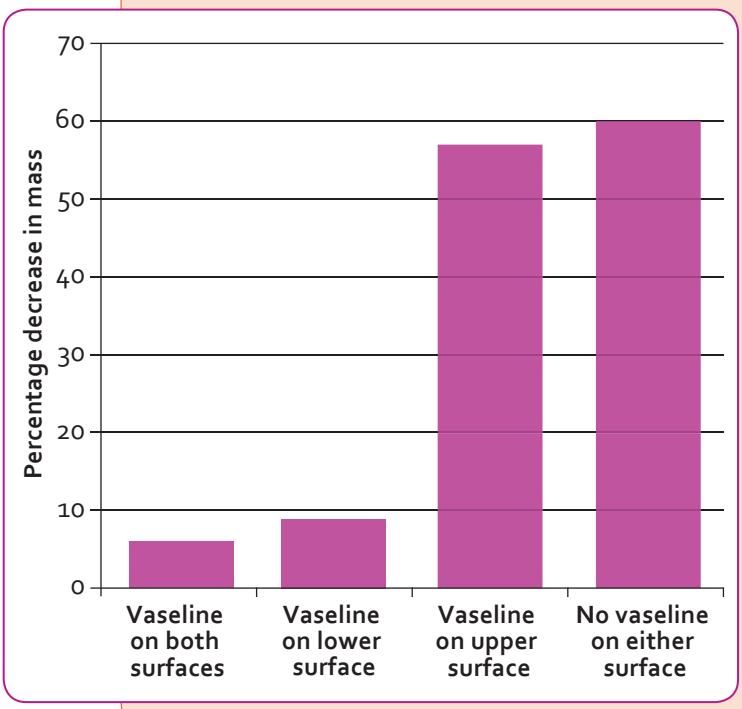
- The table has an appropriate title.
- The independent variable is in the first column. The treatments could be in any order as it is a qualitative variable; but in this case the treatments have been arranged to show the trend in the dependent variable (percentage decrease in mass).
- The second and third columns show the measurements made of the dependent variable.
- The final column shows the processed results as a percentage decrease for the dependent variable.

Percentage decrease in mass of plant leaves 4 days after being given surface treatments of Vaseline

Experimental treatment	*Initial mass of 5 leaves (g)*	*Mass of 5 leaves after 4 days (g)*	*Percentage decrease in mass*
Vaseline on both surfaces	1.68	1.58	5.95%
Vaseline on lower surface	1.81	1.64	9.39%
Vaseline on upper surface	1.64	0.71	56.71%
No Vaseline on either surface	1.72	0.68	60.47%

The data is plotted in the bar chart below.

Percentage decrease in mass of plant leaves 4 days after being given surface treatments with vaseline.



Notice that:

- The bar chart has an appropriate title.
- The dependent variable (percentage decrease in mass) is plotted on the Y (vertical) axis.
- The Y axis is labelled with the variable and its units and has a scale that avoids excess empty space.
- The independent variable is arranged at regular spaced intervals on the X (horizontal) axis.
- The X axis has no units as it is a qualitative variable comprising of discrete categories (the four experimental treatments).
- The bars representing the four discrete categories of the qualitative variable have spaces between them. Bars may be adjacent to each other if they are the same category. For example a similar experiment with the same four treatments could compare examples of deciduous and evergreen leaves. The deciduous and evergreen leaves would be adjacent bars for each discrete treatment on the X axis.
- The bars have been arranged in order to show the ascending trend in the dependent variable.
- It is not appropriate to show error bars for this particular data.

THEORY BOX 5 - CONTINUED

Variation in raw data

For example a student investigating the growth of field grown barley plants measured the height of a sample of 8 barley plants from two different fields on the same day in mid May. The raw data is shown below.

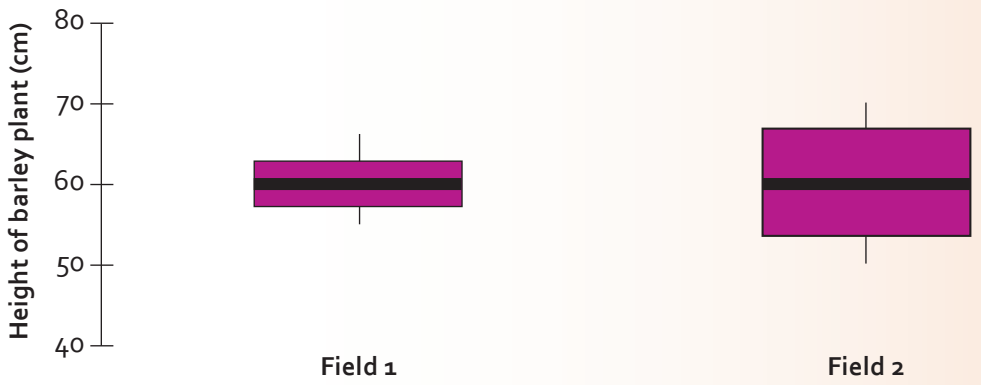
Notice that:
- The table has an appropriate title.
- The measurements are arranged in order.
- Both samples have the same mean height.

Height of barley plants from two different fields

	Height of barley plant (cm)								
Sample	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***Mean***
Field 1	55	55	58	59	60	62	65	66	60
Field 2	50	52	54	60	61	67	67	69	60

The data is plotted in a box plot below.

Height of barley plants from two different fields



Notice that:
- The box plot has an appropriate title.
- The dependent variable (plant height) is plotted on the Y (vertical) axis (in box plots the dependent variable may also be plotted on the X (horizontal) axis).
- The Y axis is labelled with the variable and its units and has a scale that avoids excess empty space.
- The samples are arranged at regular spaced intervals on the X (horizontal) axis as they have no units and are distinct categories.
- The box plot shows the minimum, lower quartile, median, upper quartile and maximum values of the data.
- The box shows the middle half of the data (the inter quartile range), the 'whiskers' show the upper and lower quartiles. The box plot as a whole shows the median and range of the data.
- It is acceptable to show the mean as well as the median - be careful to label both accordingly if this is the case!
- The variation in the raw data shown by the box plots provides more information than is seen in a mean value. This information can be valuable when comparing samples, replicates or repeated measures as part of the analysis of your results.

3.2.4 Other graphical forms

Other forms for presenting results graphically may also be used. As these are more likely to be used in a minority of biological investigations, brief notes on each of them are given below. Should you think they may be of use in presenting your data, you should discuss with your teacher/lecturer and consult other resources on their detailed use.

- Pie charts are useful for displaying proportions of a whole (for example the proportions of different prey species taken by a predator).
- Histograms are used to display the distribution of a large data set for a quantitative variable to look for a normal distribution, outliers, skewness etc (for example in the age or size of individuals in a population). If planning to use histograms, recording the raw data in a stem and leaf diagram can be helpful in determining suitable intervals for the bars (bin width) on the X axis.
- Kite diagrams are used to display the distribution and abundance of organisms along a transect line in ecological sampling.
- Logarithmic graphs are used to plot variables with a large range of values. For example a logarithmic scale on the Y axis is useful when plotting the exponential growth of a population of microorganisms.
- Scatter diagrams are used to investigate the relationship between two variables where there is no dependent variable (for example comparing the height and weight of a group of individuals). Both variables are measured and the scatter diagram (which looks much like a line graph plot) is analysed to see if there is a correlation between the variables. If the relationship is linear, it may be possible to draw a line of best fit.

THEORY BOX 6

Presenting Data in Other Graphical Forms

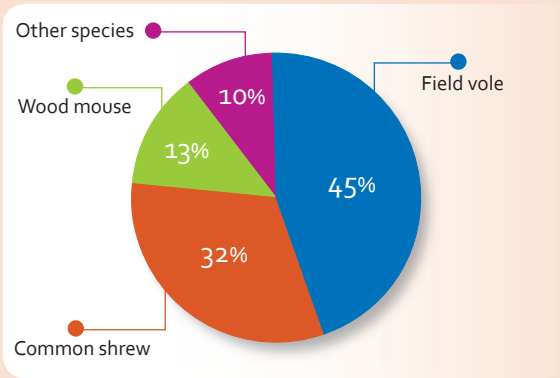
Pie charts

Pie charts are useful for displaying data for qualitative variables where the categories are proportions of a whole. In such cases they can be used as an alternative to bar charts. Pie charts are useful for around six or less fairly large categories.

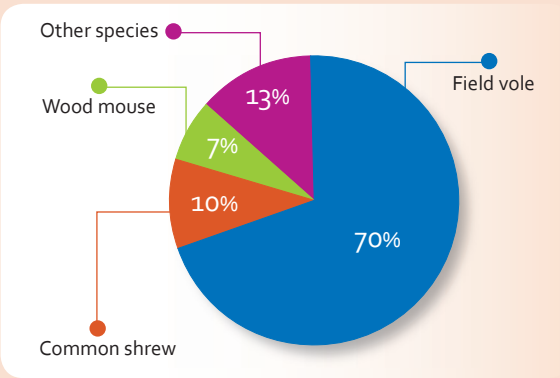
More or smaller categories may result in the pie chart becoming cluttered and difficult to interpret and it may be better to consider an alternative way to present the data.

The pie charts below show the result of a student's investigation into the composition of prey species in barn owl pellets in summer and winter.

Percentage prey species: Barn owl pellets - summer



Percentage prey species: Barn owl pellets - winter



Notice that:

- Every 1% contribution to the sector of the pie chart corresponds to an angle of 3.6 degrees.
- The sectors of the pie chart are arranged clockwise in order of magnitude.
- 'Others' are usually placed last in the order despite their size.
- The sectors are labelled with their category and percentage.
- Where two pie charts are displayed they maintain the order of the first pie chart even if the second has a different order of magnitude.

THEORY BOX 6 - CONTINUED

Histograms

Histograms are used to display relatively large data sets for a quantitative variable. They are an alternative to box plots. Box plots are useful for smaller data sets and for comparing data sets, histograms are useful for showing more detail in the distribution of the measured values. If planning to present data in a histogram it is best to record your data in a stem and leaf diagram. This will help you chose suitable intervals for the bars (bin widths) in your histogram.

For example a student measured the lengths of a sample of earthworms from a garden soil that was heavily enriched with organic matter. The results are shown in the stem and leaf diagram opposite.

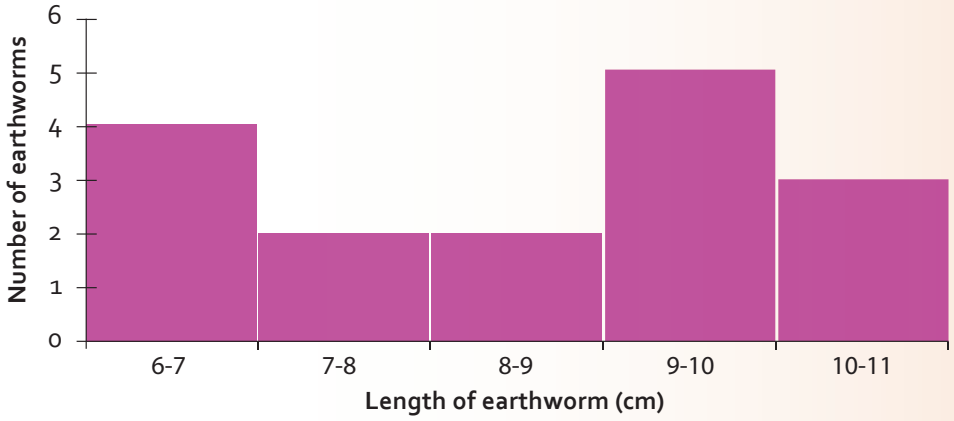
The lengths of the worms were measured in centimetres. The 'stem' and 'leaf' is formed by splitting the number into two parts - in this case before and after the decimal point. In this case the top line consists of 6.2, 6.2, 6.5 and 6.6 cm.

Length of earthworms (cm) from garden soil enriched with organic matter

Stem	*Leaves*
6	2 2 5 6
7	0 2
8	8 9
9	6 7 8 8 9
10	2 3 3

The data is plotted in the histogram below:

Length of earthworms from garden soil enriched with organic matter



Notice that:

- The histogram has a suitable title.
- The dependent variable (number in each column/bin) is plotted on the Y (vertical axis).
- The Y axis is labelled with the variable and its units and has a scale that avoids excess empty space.
- The X axis is labelled with the variable (length of earthworm) and its units (cm).
- The scale on the X axis is divided into classes (bins). The boundary values of the bins are rounded up (in this case 6.0 is in bin 6-7, 7.0 is in bin 7-8 etc).
- As the X axis is a continuous numerical scale there are no gaps between the bins (although some bins could be empty). If the variable on the X axis was measured in whole numbers, the number would be in the middle of the bin with no gaps between the bins.
- The bins are of equal width. Histograms do not need to have bins of equal width but it is better to do so as then the heights of the bars are proportionate to the number in each bin.
- The bin widths show the distribution of the data. If the bin widths were smaller or larger they may not show the data distribution. Starting with a stem and leaf plot will help you to select an appropriate bin width.

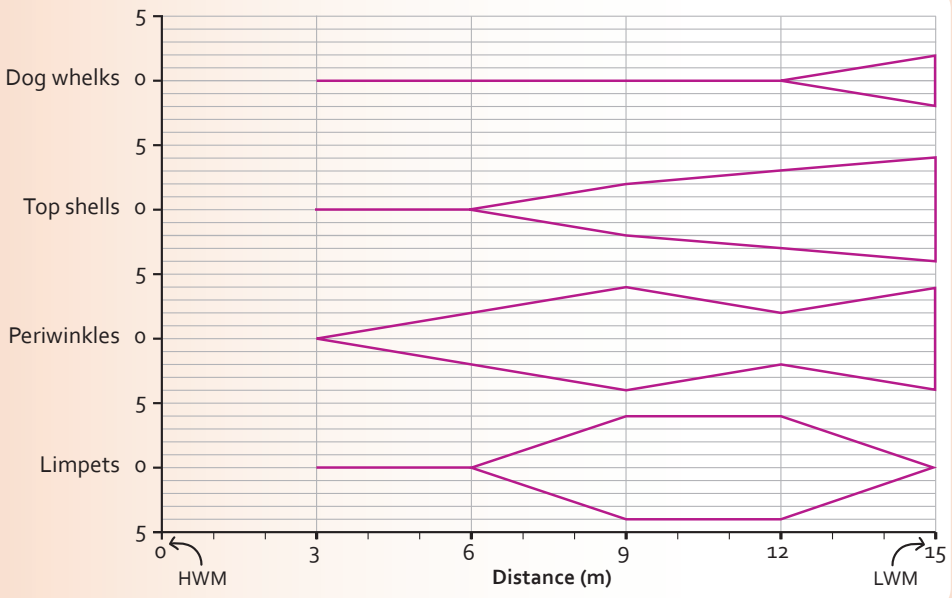
THEORY BOX 6 - CONTINUED

Kite diagrams
Kite diagrams provide a graphical display of the distribution of organisms along a transect line where an ecological variable is changing. Samples are usually taken at regular intervals along the transect using quadrat or point line sampling. Point line sampling is where species present are recorded at regular points along a line at right angles to the transect line. Species present can be recorded as a total count, percentage cover or a five point abundance scale.

For example a student measured the vertical distribution of molluscs on a transect of a rocky shore from high water mark (HWM) to low water mark (LWM). The results are shown in the kite diagram below.

Notice that:
- The kite diagram has a suitable title.
- The X axis shows the position and length of the transect.
- Each species has its own individual Y axis.
- Each Y axis has a mid line (whose value is 0) and the abundance value (1 to 5) is plotted symmetrically to both sides of the mid line.
- The points are joined by straight lies to form the 'kite' shape.
- There is a key to show the scale for the Y axis.

Distribution of marine molluscs from high water mark to low water mark on a rocky shore



Abundance scale:
1 = rare (R)
2 = occasional (O)
3 = frequent (F)
4 = common (C)
5 = abundant (A)

THEORY BOX 6 - CONTINUED

Logarithmic graphs

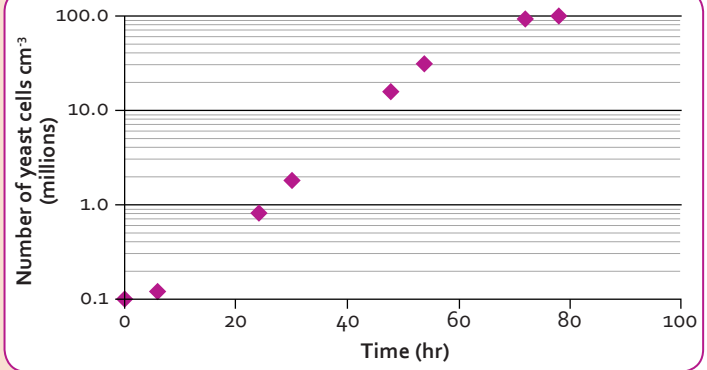
When one variable has a large range of values compared to the other variable, it can be useful to plot the variable with the large number of values on a logarithmic scale and the other variable on a numerical scale.

For example a student investigating exponential growth in a culture of yeast took cell counts at regular time intervals. He plotted the number of cells on the Y (vertical) axis as a logarithmic scale and time as a numerical scale on the X (horizontal) axis. The results are shown in the semi logarithmic (log/linear) graph opposite.

Notice that:

- The graph has a suitable title.
- The Y axis shows cell counts (the dependent variable) on a logarithmic scale.
- The X axis shows time (the independent variable) on a numerical scale.
- The axes are labelled with the variables and their units.
- The plotted points are more evenly spaced on the logarithmic scale of the Y axis than they would be on a numerical scale.
- The Y axis requires less graph space with a logarithmic scale than with a numerical scale.
- The growth curve is a straight line rather than the exponential curve found in a graph with two numerical scales.

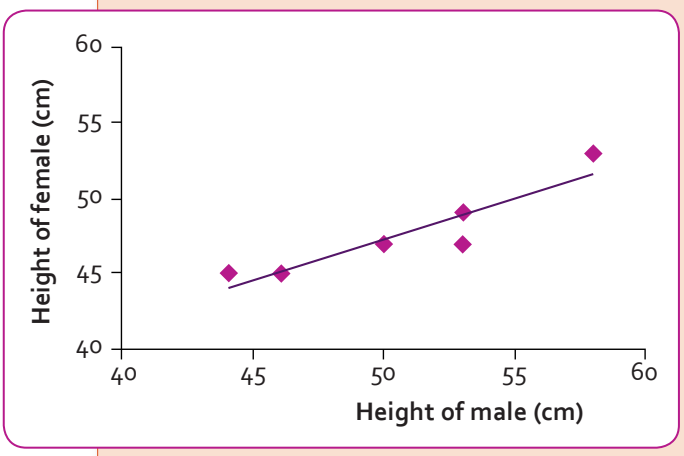
Growth of yeast cells in culture



Scatter diagrams

A scatter diagram is used where both variables are measured, i.e. there is no independent variable. Analysis of the scatter plot is used to see if there is a correlation between the two variables but cannot provide evidence of cause and effect. If a line of best fit can be drawn, it may show positive correlation (a rising line), negative correlation (a falling line) or no correlation (no evident line).

Size of male and female penguins in breeding pairs



For example a student measured the size of breeding pairs of penguins in a zoo to see if there was a correlation between the sizes of the two sexes. The results are shown in the scatter diagram below.

Notice that:

- The scatter diagram has a suitable title.
- The axes are labelled with the variable (sex) and units (cm).
- Either variable could be on the X and Y axes as there is no independent and dependent variables.
- The scales for the axes have been selected to avoid excess empty space on the graph.
- A line of best fit has been drawn that shows a positive correlation (that is penguins pair with a male/female of similar size).

Further evidence of the degree of correlation in this data could be established by using a suitable statistical test to determine a coefficient of correlation (e.g Spearman's rank correlation test).

3

3.3 STATISTICS

Key points

- *Statistical methods include descriptive and inferential statistics.*
- *Descriptive statistics are used to summarise raw data.*
- *Methods of descriptive statistics include calculating mean, mode and median values and standard deviations; tabulating data and drawing graphs.*
- *Inferential statistics use statistical tests to test for significant differences between data sets for experimental treatments or samples.*
- *Confidence intervals in tables and error bars on graphs are used to show the variability of data around a mean.*
- *The choice of statistical test to use should be made at the experimental design stage, not after you have collected your data.*

Students (and teachers) often get concerned about the use of statistics to analyse data. The mathematics that underpins statistics can be complex and difficult to understand. However for the biology investigator it is an appreciation of what the statistics can do, rather than how they work, that is of value when analysing results.

Tabulating data, drawing graphs, calculating values such as mean, median, mode and standard deviation are all referred to as *descriptive statistics* and have been described in the sections above. Descriptive statistics are useful for summarising data and for assessing the variation in samples and sets of replicates. Their use helps us to see trends and patterns and to draw conclusions from the data.

Statistical tests, sometimes called *inferential statistics*, involve complex calculations that enable us to compare differences between experimental treatments or samples to see if they are likely to have occurred as a result of variation in the data or if they are a treatment effect. The use of spreadsheets and statistical software has now made carrying out


Image: Patrisyu/FreeDigitalPhotos.net

statistical tests a straightforward matter of entering values into the appropriate software package. If the statistics show a treatment effect then the results are said to be statistically significant. A *statistically significant* result is one where there is a less than 5% probability that it has occurred by chance alone. Confidence intervals or error bars indicate the variability of data around a mean. In general, if the means being compared differ sufficiently for their confidence intervals or error bars not to overlap then the data can be said to be different. Even if a test shows there is no statistically significant effect because the error bars overlap you cannot necessarily conclude that there is no effect. It may be that the effect is too small or you do not have sufficient replicates for the statistical test to reveal it.

The type of test you carry out will depend upon whether you are investigating quantitative or qualitative variables and your experimental design. That is why the time to decide on how to analyse your results is at the experimental design stage and not once you have collected your data. When researching the techniques to use in your experimental design you should also identify what statistical tests you may wish to use later (if any). The main types of statistical test include looking for the difference between predicted and expected values (e.g. chi-squared test), comparing mean values (e.g. t-test or analysis of variance) and looking for correlation between variables (e.g Spearman's rank correlation test).

4 Evaluating Experimental Designs

Key points

- *Check the validity and reliability of your experimental design.*
- *Use a pilot study or initial experimental trials to test validity and reliability of experimental designs.*
- *To be valid your experimental design should:*
  - *have suitable variables that test your aim, question or hypothesis*
  - *have suitable controls (negative and/or positive)*
  - *control or measure any confounding variables*
  - *allow the results to be analysed to show the effects sought in the aim and hypotheses.*
- *To be reliable your experimental design should:*
  - *have sufficient replicates*
  - *use properly calibrated measuring instruments*
  - *provide results that are precise and accurate*
  - *have samples that are representative of the population*
  - *remove the possibility of observer bias*
  - *repeat experiments.*

Evaluating an experimental design involves checking its validity and reliability. An experimental design that does not test the intended aim or hypothesis is invalid. Once you have come up with a design you should always check that it tests what you set out to do in your aims and hypotheses. You can do this theoretically when you write down your design and then test it practically in your initial experiments or pilot study. If the design does not match the aim, the design can be altered accordingly or you can modify your aim to better match the experimental design. Whichever way you approach this is fine, it is all part of fine tuning your investigation.

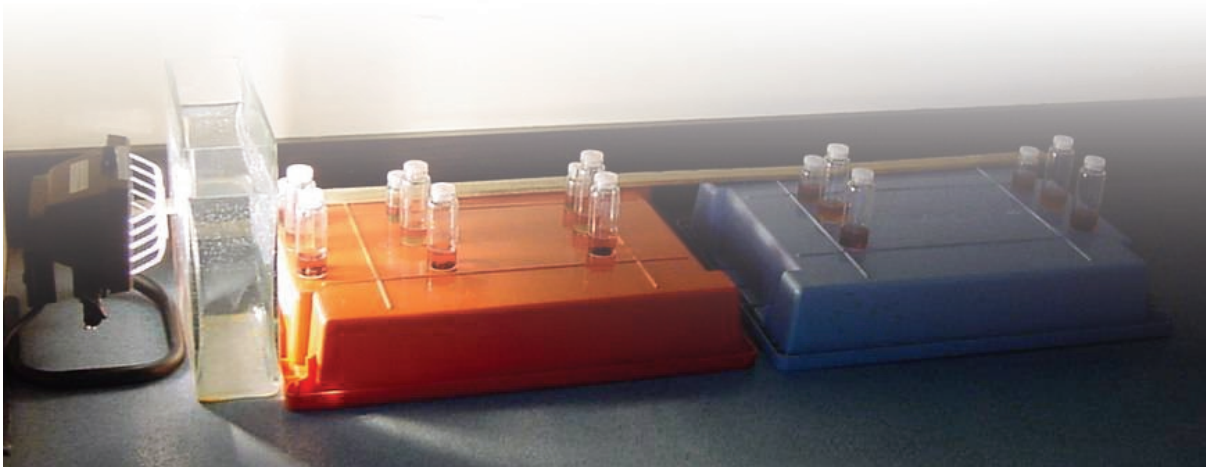
Other aspects of an experimental design to check for validity include:

- Are the experimental treatments relevant to the study/appropriate for the suggested hypotheses?
- Are there sufficient and appropriate controls to show effects?
- Can the anticipated results be analysed to show effects that: (i) meet the aims of the investigation, (ii) confirm or refute hypotheses?
- Have confounding variables been controlled or measured?
- Are the categories chosen for qualitative variables appropriate for the study?

When checking for reliability, aspects to consider include:

- Have sufficient replicates been used to give reliable results?
- Have measurements been checked for precision and accuracy?
- Have measuring instruments been calibrated?
- Has account been taken of the natural variation in samples and replicates?
- Are samples representative of the population?
- Have measures been taken to remove observer bias?
- Have experiments been repeated?

Validity and reliability should be uppermost in your mind at the planning stage. Initial experiments and pilot studies are the time to test and address these questions of validity and reliability. Time spent on this at an early stage will prevent heartache later on!



5 Drawing Conclusions

Key points

- *Write down what each set of results shows.*
- *Write down any patterns, trends, and evidence of causes or correlation that your results show overall.*
- *Write down any comments on the validity and reliability of your experimental design.*
- *Refer back to the aim, questions and hypotheses of your investigation and to the background information you researched for the introduction to your investigation report.*
- *Use all of this information to write a discussion of your findings.*
- *Draw your conclusions.*

Image: Stuart Miles/FreeDigitalPhotos.net

Drawing conclusions from an investigation as a whole is much more challenging than drawing a conclusion from an individual experiment. Consequently it is best to take a methodical approach to analysing your data when drawing conclusions. Once you have decided on the best way to present the results from each individual experiment or study in your investigation, you should write a statement of what each set of results shows. Although this will not be part of your final report it will make writing the discussion part easier. Next use these statements and the results to decide if there is evidence of causation or correlation. Then evaluate your experimental design recording any strengths or weakness in terms of validity and reliability. Now you have the raw material using these three elements (experimental findings, causation/correlation, validity/reliability) from which to draw conclusions from your investigation as a whole. Finally when drawing conclusions from the investigation as a whole you should refer back to the aim and hypotheses of the investigation.

When you come to write the discussion section of your investigation report you should also relate your findings to existing knowledge and the results of other scientists' investigations; discuss the biology. The information you have gathered as background research to use in the introduction to your investigation report will help you here. You might want to comment on the relevance of your findings to scientific research and to the significance of their environmental, social or economic impact. Finally, it is often useful to describe what follow-up studies could potentially be built on the foundations of your study.

Reading and Writing Scientific Reports

6

Key points

- *Practise reading and critically analysing scientific papers and reports to become familiar with how scientific reports are written.*
- *Use the bullet list in Theory Box 7 - Publishing Scientific Results to help you develop the skills to analyse scientific papers and reports.*
- *Follow carefully the advice in the SQA Instructions for Candidates on writing an Investigation Report for the Advanced Higher Project.*

As part of your investigation studies you should be reading scientific papers and reports. By critically analysing these you will learn about how a good scientific report should be written. This will prepare you and give you practice in analysing the scientific reports and scientific data that are used in Unit and Course assessment. It will also help you when it comes to writing the report of your investigation.

Use the questions in Theory Box 7 *Publishing Scientific Results* to help develop your critical analysis skills and to develop an awareness of the requirements of scientific writing. The questions listed can also be used as a check list for your own Investigation Report for the Advanced Higher Project. Detailed advice on writing your Investigation Report is provided in the Advanced Higher Biology Instructions for Candidates published by SQA. It is essential to consult this advice both at the start of your investigation and at the writing up stage.

THEORY BOX 7

Publishing Scientific Results

Scientific papers are the most widely used means by which research findings are communicated to others. Scientific findings can also be communicated through seminars, conference presentations and posters. Scientific papers are published in journals that cover specific areas of scientific research. Although most journals are now published on-line, many are only available by subscription. Papers submitted for publication are evaluated by two or more expert reviewers in the specialist field who assess the scientific quality of the paper and make recommendations on its suitability for publication, a process known as *peer review*. It is important that scientific papers include publication of methods, data, analysis and conclusions so that others are able to repeat an experiment or study. As part of developing your skills in investigation and scientific report writing, you should read and critically evaluate scientific papers.

When critically evaluating a scientific report you should consider the following questions:

- Does the title explain clearly what the study was about?
- Does the abstract/summary give a brief summary of the aims, methods and findings to allow the reader to grasp the essence of the work?
- Does the introduction provide the necessary relevant background information, including any contradictory information, citing appropriate references to support the methods, results and discussion?
- Does the introduction explain why the study was carried out and place the study in the context of existing understanding including any ethical considerations that need to be taken into account?
- Does the introduction explain why the study methods and experimental organisms were chosen, state the aims and hypotheses of the work and make reference to any pilot studies?
- Do the methods described explain clearly what was done so that another investigator could repeat the work?
- Do the methods clearly identify the dependent and independent variables, state how confounding variables were controlled and justify sample sizes and number of replicates?
- Do the results display and describe the results obtained in a suitably summarised form from which conclusions can be readily drawn?
- Do the results make best use of tables, graphs and statistical analysis to show trends and patterns?
- Does the discussion draw conclusions and explain the significance of the results in relation to the aim and to other published work?
- Does the discussion comment on the validity and reliability of the experimental design?
- Are the conclusions drawn in the discussion valid for the presented results?
- Is the work of others acknowledged including references correctly cited in the text?

Reading scientific papers can often be challenging. This is normal as often you will not have the detailed expert background and knowledge that the authors assume their readers will have. Scientific papers generally require several readings to get to grips with their content - and even then some of it may still not be clear. This is where reflecting on the questions above can be useful; they will help you to understand the parts of the paper that are most important to you.

7 Selected Bibliography

- *Advanced Higher Biology Project: Instructions for Candidates*, SQA.
  http://sqa.org.uk

  Absolutely essential for Advanced Higher Biology candidates. Can be found in SQA *Advanced Higher Biology: Project Assessment Task*. Must be read in conjunction with this booklet.

- *Advanced Higher Biology: Project Assessment Task*, SQA.
  http://sqa.org.uk

  Essential reading for teachers/lecturers preparing candidates for Advanced Higher Biology. Contains Project marking instructions and *Instructions for Candidates*. Project marking instructions can also be found in SQA *Advanced Higher Biology Project: General assessment information*.

- *Materials of Living Origin - Educational Uses - A Code of Practice for Scottish Schools and Colleges*, SSERC, 2012.
  http://www.sserc.org.uk

  Provides advice and guidance on working with living material in the laboratory and field including Health and Safety and other relevant legislation. Essential reading for risk assessment.

- *Safety in Microbiology - A Code of Practice for Scottish Schools and Colleges*, SSERC, 2012.
  http://www.sserc.org.uk

  Provides advice and guidance on working with microorganisms. Essential reading for risk assessment.

- Biological Nomenclature, *Society of Biology*, 4th Edition, 2009.

  Full of useful information. Section 1 on Evidence and Communication is particularly relevant to investigative work.

- Jones A., Reed R., Weyers J., *Practical Skills in Biology*, 5th Edition, 2012. Pearson, Harlow.

  Contains a wealth of information on a wide range of biology practical work and study skills.

- Ruxton G.D. and Colegrave N., *Experimental Design for the Life Sciences*, 3rd Edition, 2011. Oxford University Press, Oxford.

  An introduction to experimental design and the collection of good quality data illustrated throughout by the use of practical examples in biology.

- Dytham C., *Choosing and Using Statistics*, 3rd Edition, 2010. Blackwell Science, Oxford.

  An accessible book on statistics, based on their use in biology rather than mathematics. Includes advice on using computer packages including Excel.

- Martin P. and Bateson P., *Measuring Behaviour: An Introductory Guide*, 3rd Edition, 2007. Cambridge University Press, Cambridge.

  A clear and concise practical guide to quantitative studies of animal and human behaviour.

- Chalmers N. and Parker P., *Fieldwork and Statistics for Ecological Projects: The OU Project Guide*, 2nd Edition, 1989. Field Studies Council, Shrewsbury.

  Describes a wide range of ecological fieldwork techniques with particular emphasis on planning for the statistical analysis of results. The Field Studies Council also publishes a wide range of useful and straightforward identification guides for ecological project work.

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