How to Write a Scientific Report

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You have decided to participate in the Statistics Competition. If you want to increase your chances of succeeding, these guidelines may be helpful. We will explain the basics of the scientific method and scientific reasoning and how to structure your results.

Introduction

In these guidelines, we focus on the process of scientific reasoning and how to present your ideas coherently in a written report. We do not discuss specific statistical procedures, since there are plenty of textbooks covering that and your teachers will be more than happy to help you, too.

The key to a well-written report is the *scientific method* — once you have understood it, writing up your findings will be much easier. We will also briefly discuss plots that you can use to present your data. If you stick to these, you will not run the risk of getting lost in all the different graphs that software packages offer nowadays and, as a consequence, making suboptimal choices.

Scientific method

Scientists do not arbitrarily come up with explanations and theories about how the real world works. They follow an established process called the *scientific method*, which helps to eliminate the scientists' personal and cultural biases and preferences from scientific theories. In order to write a good report for the competition, your arguments should be sound and coherent — the scientific method can help you with that.

The steps of the scientific method

When scientists do research, they typically follow a sequence of steps of reasoning, experimentation and evaluation.[1] Although there are many refinements and embellishments, the core steps can be summarised as follows:

(1) Observe a phenomena;
(2) formulate a hypothesis to explain the phenomena;
(3) use the hypothesis to make a prediction about something related to the phenomena;
(4) collect or find data to test your prediction;
(5) depending on the data, reject your hypothesis, or refine it and return to (3).

The word 'hypothesis' in this context means 'an explanation that you propose to explain a specific phenomena', and it is not directly related to the technical term 'hypothesis testing', which you may have heard being used in statistics.

If you think about it, you will realise hat the scientific method is not so much different from what we do in everyday life. However, as we shall see, there is one more crucial step. Let's illustrate this by means of an example about a fictive person called Sophia[2].

(1) We observe a phenomena: *"Hey, every time I eat satay, I get a rash around my lips"*.
(2) We formulate a hypothesis as an attempt to explain the observation: *"I think I might be allergic to peanuts and, since satay sauce contains peanuts, I get a rash whenever I eat it"*.
(3) We use the hypothesis to make a prediction: *"If I avoid eating food containing peanuts, I can prevent getting rashes"*.

[1] This section is inspired by [7]

[2] According to `sg.theasianparent.com`, 'Sophia' is the most popular baby girl name in 2012 (`sg.theasianparent.com/what-to-name-your-dragon-baby`).

In everyday life, we mostly content ourselves with Steps (1) to (3). We come up with an ad-hoc explanation based on personal experience and anecdotal evidence, and we draw conclusions from it — usually without ever testing its validity. But the scientific method differs from everyday life by adding a crucial fourth step: The prediction must be tested via *controlled experiments*. The important word here is 'controlled', which means that it can be repeated independently by other researchers.

If the experiment turns out as predicted, we will be more confident that our explanation has some truth to it. One reason science is so successful is that we don't just do this once, but different researchers repeat this procedure many times, testing many different aspects of the hypothesis, independently of each other. Every time a prediction is confirmed, our confidence in the hypothesis increases. If an experiment contradicts our prediction, we have to either reject our hypothesis or, in a fifth step, modify it.

Sophia's allergy

The hypothesis that Sophia is allergic to peanuts can be tested via experiments, but the experiment that Sophie proposes above ('stop eating any food containing peanuts') is not what we would consider a 'controlled' experiment, since it is not really repeatable. There are better experiments. For example, we could prepare ten portions of satay sauce, five with peanuts, and five with a peanut substitute (maybe cashew nuts with added artificial peanut flavour). Every day on ten consecutive days, Sophia would get one portion (she does not know which type she gets), and then her reaction would be recorded. We could do this not just with satay sauce, but also with other dishes containing peanuts.

It is important to realise that there are many ways in which Sophia's explanation and conclusion could be wrong. She could be allergic to nuts in general, not just peanuts, in which case avoiding peanuts would not completely prevent the rashes. She might be allergic to tamarind, which is sometimes added for the sour taste ('assam' in Malay). Tamarind is a member of the bean family (legumes) like peanuts, and hence may indeed cause allergic reactions in people sensitive to plants from the bean family [6]. In that case her reaction would manifest only when eating from satay stalls that use tamarind in their satay sauce. Or she might only be allergic to a combination of peanuts and tamarind.

Despite the fact that a peanut allergy seems to be the most reasonable explanation (we haven't heared of people who really are allergic to tamarind), it nevertheless requires evidence. Sometimes 'common sense' and 'logic' tempt us into believing that no test is needed to validate our explanation for a particular phenomena, but only through controlled experiments can we separate valid from invalid hypotheses.

A good example to illustrate this point is the old recommendation of avoiding calcium-rich food to prevent kidney stones. The reasoning was that the majority of kidney stones are composed of *calcium oxalate* [4], and 'common sense' mandates that reducing calcium intake by avoiding product such as milk would reduce this type of kidney stone. It turns out, however, that increasing the calcium intake in fact *reduces* the risks of kidney stones [2].

A few words about experiments

In many disciplines, such as biology, archaeology, environmental sciences, astronomy, social sciences, etc., it is not possible to perform experiments in the way just described. In such cases, researchers have to resort to collecting other forms of evidence, such as historical data or measurements of the systems under investigation.

For example, if we would like to test the hypothesis that different strains of the dengue virus differ in their symptoms, we can of course not infect people with dengue and then measure what happens. In such cases, we have to resort to collecting data from the past, do surveys, etc. in order to test our prediction. If our hypothesis is valid and the symptoms differ indeed then we should see this in medical reports. Or if we claim that global warming is mainly caused by carbon dioxide emission from humans then we can not (yet) do an experiment on another planet. Again, in this case we have to resort to historical evidence such as ice core probes, or small scale experiments such as to measure carbon dioxide absorption rates of sea water.

What this means for your report

There is one important point that you need to remember if you want your report to be successful:

> **Formulate your hypotheses and predictions *before* you collect the data, instead of giving wild explanations afterwards.**

A good scientist *first* comes up with a hypothesis and prediction and only *then* collects data to verify the prediction. Instead of just collecting data, summarising them, and then speculating about what they mean, ask yourself first, what outcome you expect and why you expect that outcome. That 'why' question most likely contains an interesting hypothesis that you can test, and the outcome you expect is nothing but your prediction! Your prediction does not have to be quantitative ("we predict that, before exams, students spend 1.2 hours less watching television than after exams"), it could well be just qualitative ("we predict that, before exams, students spend less time watching television than after exams"). In fact in many disciplines, qualitative predictions are more common than quantitative predictions. It is very important that you think about this and record your thoughts *before* you start collecting data.

As part of the discussion of your findings, you may of course propose new hypotheses or discuss modifications of your current hypothesis. You may also attempt to explain unexpected patterns in the data or features you did not specifically look out for at first. Nevertheless, if you want to do good science, you need a hypothesis at the heart of your research, derive a prediction from it, and then perform an appropriate experiment or collect other forms of evidence with which you can test your hypothesis.

Random error

No matter how well we design our experiment, we have to keep in mind that no experiment can be perfectly precise and that errors can complicate our attempt to test our predictions. There are several errors that can occur, but the most important error in particular for the statistics competition is what we call *random error*, and it is here were statistics can help us decide whether the experimental outcome is in agreement with our prediction, or contradicts it.

Again, I need to stress the main point that there is little point in doing sophisticated statistical tests and calculating p-values if you do not know what the question is! You need a prediction first, and only then does a statistical test make any sense.

The structure of a scientific publication

In order to understand how to write a good report, it is important to understand how scientists publish their findings, and your report can be structured in very much the same way. A scientific report typically consists of the following sections:

(1) Introduction,
(2) Methods,
(3) Results,
(4) Discussion,
(5) References.

It is important to understand the differences between these sections and to put information in the appropriate location.[3]

Section 'Introduction'

Get your viewer interested about the issue or question. Explain why this study is of interest and what the objectives are. In particular, this section gives some background information for the study. You can discuss results and conclusions of previously published studies (if there are any) to help explain why the current study is of interest.

The introduction is organised to move from general information to specific information. The last sentences of the introduction should be a statement of objectives and a statement of hypotheses. This will be a good transition to the next section on methods, in which you will explain how you proceeded to meet your objectives and test your hypotheses.

For example, you might write the following:

> *"Our objective was to determine if there is a relationship between the intake of tamarind extract and symptoms of peanut allergies. We hypothesised that adding tamarind extract to common dishes would trigger or increase typical allergy symptoms in people with known peanut allergies."*

Section 'Methods'

This section provides all the methodological details necessary for another scientist to duplicate your work. It should be a narrative of the steps you took in your experiment or study, not a list of instructions such as you might find in a cookbook. Briefly describe experimental equipment and procedure or where you got your data from.

This is also the section were you need to provide a brief description of statistical tests you used (statistics are methods!). Be sure not to include extraneous information, though, as scientists know all about null hypotheses and when to reject them. For example, you do not need to define the χ^2-test statistic, since that information is readily available. Just

[3] This section is a shortened and modified version of [1]

say *"We used Pearson's χ^2 test to test for independence between adding tamarind extract and allergy symptoms"*.

Section 'Results'

This section presents the results of the experiment, but does not attempt to interpret their meaning — hold all discussion of the significance of the results for the discussion section. As with the methods section, the trick to writing a good results section is knowing what information to include or exclude. You will not present the raw data that you collected, but rather you will summarise the data with text, tables and figures. Use text to state the results of your study, then refer the reader to a table or figure where they can see the data for themselves. For example you may write:

> *"Tamarind extract did not significantly trigger typical allergy symptoms in people with known peanut allergies (df = 56, $p > 0.1$), regardless of the amount and the dish to which it was added (Table 1). Allergy symptoms were significantly associated with the use of peanut extracts in the same type of dishes (df = 52, $p = 0.02$, Table 2)."*

The sentences above are well written because: (i) the sentences are short and concise, (ii) the words 'significantly' and 'not significantly' are accompanied by the corresponding *p*-values and degrees of freedom (sample size) of the tests used, and (iii) the reader is referred to a table where the data to support the statement can be found.

It is best to present the data in a table unless there is visual information that can be gained by using a figure. For example, a figure is useful for reporting a regression analysis (line graph), or comparing the several treatment levels (bar charts). Each table and figure has several lines of text in the legend (or caption) that explain the information that is being presented; this is, they are made to stand alone. If your table includes the results of a statistical analysis, be sure to provide the information necessary for the reader to properly evaluate the analysis (degrees of freedom, sample size, etc.).

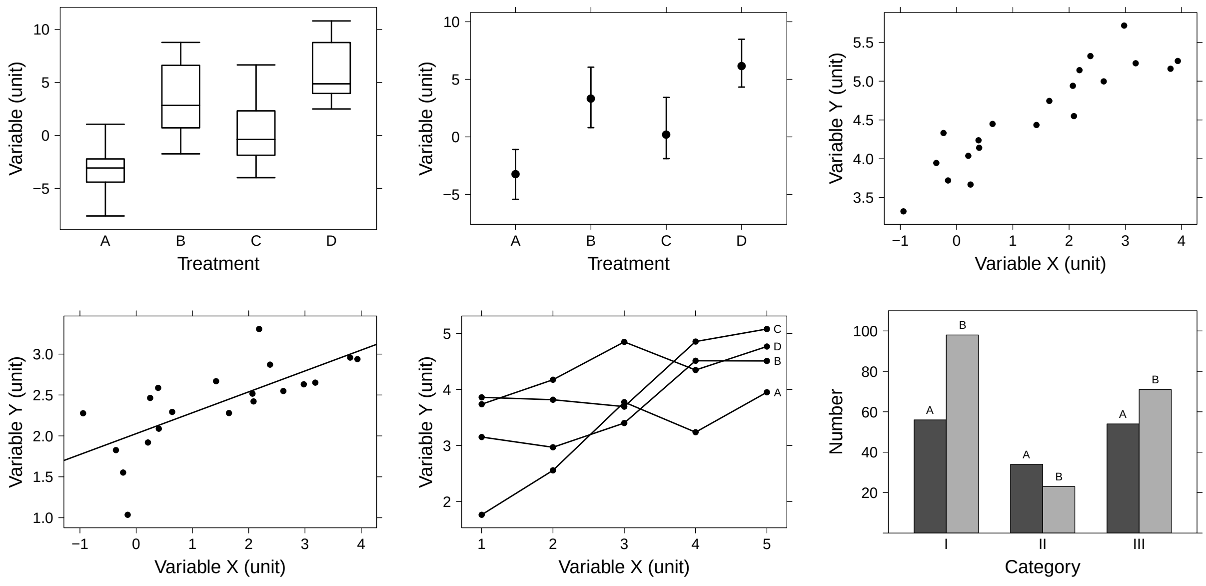
It is not necessary to describe every step of your statistical analyses. Scientists understand all about null hypotheses, rejection rules, and so forth and do not need to be reminded of them. Likewise, cite tables and figures without describing in detail how the data were manipulated.

In order to present the (summarised) data, we recommend that you chose among the following six types of graphs (see Figure 1).

- Use *box plots* to displays medians. The 'box' contains 50% of the data points, and the middle line of the box is the median. The tips of the projecting bars show minimum and maximum values (or certain quantiles — be sure you know which one your software is plotting). Explain graph elements in the figure legend. Comparisons of medians can be done with Wilcoxon rank sum tests, Wilcoxon signed rank tests, and Kruskal-Wallis tests, among many others.
- Related to box plots are *confidence interval plots* to show estimated means. Error bars can be standard errors, standard deviations, etc., so be sure to specify which in the figure legend. Comparison of means can be done with unpaired Student's t-test, ANOVA, etc.
- Use *scatterplots* to show relationships (correlations) between continuous variables. You can provide a correlation coefficient and statistical significance either in the figure legend or directly next to your cloud of points.
- Use *regression plots* to display how one variable causes variation in a second variable (Y-axis). As for correlation analysis, you can put the details in the figure legend, but it is better to situate your findings in a graphical way on your graph.
- You can use *line charts* instead of scatterplots if your X-axis represents a continuous variable and your experiment measured X at consecutive values (for example X could be time and your experiment measures blood pressure Y at five consecutive days on different patients). Only connect the points that belong together. Don't use line charts if the X-axis represents unordered categories.
- Use *bar charts* to show proportions in count (that is, discrete and discontinuous) data. Bar charts are not appropriate for displaying means. Make sure your Y-axis starts in 0, otherwise you are misleading the reader. You can compare counts with goodness of fit tests and contingency chi-square tests, for example.

There are few reasons to use anything else than the few plots mentioned above. Avoid pie charts; instead, use bar charts to show proportions. And at all costs, do not use unnecessary 3D effects in your plots, in particular do not use 3D pie charts, 3D bar or pyramid charts! The third dimension usually bears

Figure 1: *Different types of graphs to present data. Top line from left to right: box plot, confidence interval plot, scatterplot; bottom line from left to right: regression plot, line chart, bar plot (make sure the Y-axis in the bar plot starts at 0).*



absolutely no information or may even be misleading, and therefore does not belong into a graph!

Section 'Discussion'

In this section, you are free to explain what the results mean. Relate your discussion back to the objectives and questions you raised in the introduction section. However, do not simply re-state the objectives. Make statements that synthesise all the evidence (including previous work and the current work).

Do not make statements that are too broad: it is unlikely, for example, that through one experiment alone, you will discover that tamarind does not cause any allergies. Limit your conclusions to those that your data can actually support, such as

> *"We did not find a significant effect of tamarind extract on people with known peanut allergy in this experiment."*

You can then proceed to speculate on why this occurred and whether you expected this to occur.

If necessary, note problems with the methods and explain anomalies in the data. Do not simply list the problems but provide thoughtful discussion about the implications of the errors in terms of your conclusions.

Section 'References'

This is the last section of the paper. Here you should provide a list of all the published work you cited in the report and sources of data.

Optional section 'Acknowledgments'

Thank individuals for specific contributions (equipment donation, statistical advice, comments on earlier versions of the report, your teachers).

Other tips

Here a list of general and specific tips to write your report.[4]

- When reporting numbers, just give a few significant digits. In most situations, the number '6.38' is as good as '6.37811345'.
- Use italics to emphasise a word instead of underlining it.
- Give your graphs titles or informative phrases.
- Do not include the same data in both a table and a figure; only use either one.
- Most graphing applications automatically give your graph a key, but it is better to directly label the different graph elements with the text tool, rather than using keys.

[4] This section is a shortened and modified version of [3]; the templates in Figures **??** and **??** are modified versions of those of [3]

- Avoid giving your graphs coloured backgrounds, grid lines, or boxes. If your graphing program gives them to you automatically, remove them.
- Do not display two-dimensional data in 3D. Three-dimensional graphs may look 'professional' to the layperson, but they obscure true differences among bar heights.
- Avoid pie charts because humans are not very good at comparing areas. Use bar plots instead to illustrate proportions.
- Avoid a specific section 'Further directions'. This belongs into the discussion section. Only suggest further directions if you really think it contributes to the report and only if they are directly relevant to your study. You need to explain why the further directions are important and/or of any interest, but be brief.

References

[1] *A Guide to Writing in the Biological Sciences.* George Mason University, Department of Biology. Available at `classweb.gmu.edu/biologyresources/writingguide`.

[2] Milk Myth Buster: Drinking milk does not cause kidney stones, and may in fact protect against them. Dairy Council of California. Available at `www.healthyeating.org/Milk-Dairy/Milk-Myth-Busters.aspx` (this reference may be a bit biased)

[3] C. Purrington. *Designing conference posters.* Available at `colinpurrington.com/tips/academic/posterdesign`

[4] Kidney stone. (2013, July 13). In *Wikipedia, The Free Encyclopedia.*

[5] Tamarind. (2013, July 5). In *Wikipedia, The Free Encyclopedia.*

[6] Tamarind spice allergy. Livestrong.com. Available at `www.livestrong.com/article/446772-tamarind-spice-allergy`

[7] F. L. H. Wolfs. *Introduction to the scientific method.* Available at `teacher.nsrl.rochester.edu/phy\_labs/AppendixE/AppendixE.html`.