

1. Categorical data analysis

Now that we've covered the basic theory behind hypothesis testing it's time to start looking at specific tests that are commonly used in psychology. So where should we start? Not every textbook agrees on where to start, but I'm going to start with " χ^2 tests" (this chapter, pronounced "chi-square"*1) and " t -tests" (Chapter ??). Both of these tools are very frequently used in scientific practice, and whilst they're not as powerful as "regression" (Chapter ??) and "analysis of variance" (Chapter ??) they're much easier to understand.

The term "categorical data" is just another name for "nominal scale data". It's nothing that we haven't already discussed, it's just that in the context of data analysis people tend to use the term "categorical data" rather than "nominal scale data". I don't know why. In any case, **categorical data analysis** refers to a collection of tools that you can use when your data are nominal scale. However, there are a lot of different tools that can be used for categorical data analysis, and this chapter covers only a few of the more common ones.

1.1

The χ^2 (chi-square) goodness-of-fit test

The χ^2 goodness-of-fit test is one of the oldest hypothesis tests around. It was invented by Karl Pearson around the turn of the century (**Pearson1900**), with some corrections made later by Sir Ronald Fisher (**Fisher1922**). It tests whether an observed frequency distribution of a nominal variable matches an expected frequency distribution. For example, suppose a group of patients has been undergoing an experimental treatment and have had their health assessed to see whether their condition has improved, stayed the same or worsened. A goodness-of-fit test could be used to determine whether the numbers in each category - improved, no change, worsened - match the

*1Also sometimes referred to as "chi-squared"

numbers that would be expected given the standard treatment option. Let's think about this some more, with some psychology.

1.1.1 The cards data

Over the years there have been many studies showing that humans find it difficult to simulate randomness. Try as we might to “act” random, we *think* in terms of patterns and structure and so, when asked to “do something at random”, what people actually do is anything but random. As a consequence, the study of human randomness (or non-randomness, as the case may be) opens up a lot of deep psychological questions about how we think about the world. With this in mind, let's consider a very simple study. Suppose I asked people to imagine a shuffled deck of cards, and mentally pick one card from this imaginary deck “at random”. After they've chosen one card I ask them to mentally select a second one. For both choices what we're going to look at is the suit (hearts, clubs, spades or diamonds) that people chose. After asking, say, $N = 200$ people to do this, I'd like to look at the data and figure out whether or not the cards that people pretended to select were really random. The data are contained in the `randomness.csv` file in which, when you open it up in JASP, you will see three variables. These are: an `id` variable that assigns a unique identifier to each participant, and the two variables `choice_1` and `choice_2` that indicate the card suits that people chose.

For the moment, let's just focus on the first choice that people made. We'll use the [Frequency tables](#) option under 'Descriptives' - 'Descriptive Statistics' to count the number of times that we observed people choosing each suit. This is what we get:

clubs	diamonds	hearts	spades
35	51	64	50

That little frequency table is quite helpful. Looking at it, there's a bit of a hint that people *might* be more likely to select hearts than clubs, but it's not completely obvious just from looking at it whether that's really true, or if this is just due to chance. So we'll probably have to do some kind of statistical analysis to find out, which is what I'm going to talk about in the next section.

Excellent. From this point on, we'll treat this table as the data that we're looking to analyse. However, since I'm going to have to talk about this data in mathematical terms, it might be a good idea to be clear about what the notation is. In mathematical notation, we shorten the human-readable word “observed” to the letter O , and we use subscripts to denote the position of the observation. So the second observation in our table is written as O_2 in maths. The relationship between the English descriptions and the mathematical symbols are illustrated below:

label	index, i	math. symbol	the value
clubs, ♣	1	O_1	35
diamonds, ♦	2	O_2	51
hearts, ♥	3	O_3	64
spades, ♠	4	O_4	50

Hopefully that's pretty clear. It's also worth noting that mathematicians prefer to talk about general rather than specific things, so you'll also see the notation O_i , which refers to the number of observations that fall within the i -th category (where i could be 1, 2, 3 or 4). Finally, if we want to refer to the set of all observed frequencies, statisticians group all observed values into a vector^{*2}, which I'll refer to using boldface type as \mathbf{O} .

$$\mathbf{O} = (O_1, O_2, O_3, O_4)$$

Again, this is nothing new or interesting. It's just notation. If I say that $\mathbf{O} = (35, 51, 64, 50)$ all I'm doing is describing the table of observed frequencies (i.e., **observed**), but I'm referring to it using mathematical notation.

1.1.2 The null hypothesis and the alternative hypothesis

As the last section indicated, our research hypothesis is that "people don't choose cards randomly". What we're going to want to do now is translate this into some statistical hypotheses and then construct a statistical test of those hypotheses. The test that I'm going to describe to you is **Pearson's χ^2 (chi-square) goodness-of-fit test**, and as is so often the case we have to begin by carefully constructing our null hypothesis. In this case, it's pretty easy. First, let's state the null hypothesis in words:

H_0 : All four suits are chosen with equal probability

Now, because this is statistics, we have to be able to say the same thing in a mathematical way. To do this, let's use the notation P_j to refer to the true probability that the j -th suit is chosen. If the null hypothesis is true, then each of the four suits has a 25% chance of being selected. In other words, our null hypothesis claims that $P_1 = .25$, $P_2 = .25$, $P_3 = .25$ and finally that $P_4 = .25$. However, in the same way that we can group our observed frequencies into a vector \mathbf{O} that summarises the entire data set, we can use \mathbf{P} to refer to the probabilities that correspond to

^{*2}A vector is a sequence of data elements of the same basic type

our null hypothesis. So if I let the vector $\mathbf{P} = (P_1, P_2, P_3, P_4)$ refer to the collection of probabilities that describe our null hypothesis, then we have:

$$H_0: \quad \mathbf{P} = (.25, .25, .25, .25)$$

In this particular instance, our null hypothesis corresponds to a vector of probabilities \mathbf{P} in which all of the probabilities are equal to one another. But this doesn't have to be the case. For instance, if the experimental task was for people to imagine they were drawing from a deck that had twice as many clubs as any other suit, then the null hypothesis would correspond to something like $\mathbf{P} = (.4, .2, .2, .2)$. As long as the probabilities are all positive numbers, and they all sum to 1, then it's a perfectly legitimate choice for the null hypothesis. However, the most common use of the goodness-of-fit test is to test a null hypothesis that all of the categories are equally likely, so we'll stick to that for our example.

What about our alternative hypothesis, H_1 ? All we're really interested in is demonstrating that the probabilities involved aren't all identical (that is, people's choices weren't completely random). As a consequence, the "human friendly" versions of our hypotheses look like this:

H_0 : All four suits are chosen with equal probability

H_1 : At least one of the suit-choice probabilities *isn't* 0.25

and the "mathematician friendly" version is:

$$H_0: \quad \mathbf{P} = (.25, .25, .25, .25)$$

$$H_1: \quad \mathbf{P} \neq (.25, .25, .25, .25)$$

1.1.3 The "goodness-of-fit" test statistic

At this point, we have our observed frequencies \mathbf{O} and a collection of probabilities \mathbf{P} corresponding to the null hypothesis that we want to test. What we now want to do is construct a test of the null hypothesis. As always, if we want to test H_0 against H_1 , we're going to need a test statistic. The basic trick that a goodness-of-fit test uses is to construct a test statistic that measures how "close" the data are to the null hypothesis. If the data don't resemble what you'd "expect" to see if the null hypothesis were true, then it probably isn't true. Okay, if the null hypothesis were true, what would we expect to see? Or, to use the correct terminology, what are the **expected frequencies**. There are $N = 200$ observations, and (if the null is true) the probability of any one of them choosing a heart is $P_3 = .25$, so I guess we're expecting $200 \times .25 = 50$ hearts, right? Or, more specifically, if we let E_i refer to "the number of category i responses that we're expecting if the null is true", then

$$E_i = N \times P_i$$

This is pretty easy to calculate. If there are 200 observations that can fall into four categories, and we think that all four categories are equally likely, then on average we'd expect to see 50 observations in each category, right?

Now, how do we translate this into a test statistic? Clearly, what we want to do is compare the *expected* number of observations in each category (E_i) with the *observed* number of observations in that category (O_i). And on the basis of this comparison we ought to be able to come up with a good test statistic. To start with, let's calculate the difference between what the null hypothesis expected us to find and what we actually did find. That is, we calculate the "observed minus expected" difference score, $O_i - E_i$. This is illustrated in the following table.

		♣	◇	♡	♠
expected frequency	E_i	50	50	50	50
observed frequency	O_i	35	51	64	50
difference score	$O_i - E_i$	-15	1	14	0

So, based on our calculations, it's clear that people chose more hearts and fewer clubs than the null hypothesis predicted. However, a moment's thought suggests that these raw differences aren't quite what we're looking for. Intuitively, it feels like it's just as bad when the null hypothesis predicts too few observations (which is what happened with hearts) as it is when it predicts too many (which is what happened with clubs). So it's a bit weird that we have a negative number for clubs and a positive number for hearts. One easy way to fix this is to square everything, so that we now calculate the squared differences, $(O_i - E_i)^2$. As before, we can do this by hand:

		♣	◇	♡	♠
expected frequency	E_i	50	50	50	50
observed frequency	O_i	35	51	64	50
difference score	$O_i - E_i$	-15	1	14	0
squared difference	$(O_i - E_i)^2$	225	1	196	0

Now we're making progress. What we've got now is a collection of numbers that are big whenever the null hypothesis makes a bad prediction (clubs and hearts), but are small whenever it makes a good one (diamonds and spades). Next, for some technical reasons that I'll explain in a moment, let's also divide all these numbers by the expected frequency E_i , so we're actually calculating the *scaled* squared difference, $\frac{(E_i - O_i)^2}{E_i}$. Since $E_i = 50$ for all categories in our example, it's not a very interesting calculation, but let's do it anyway:

		♣	◇	♡	♠
expected frequency	E_i	50	50	50	50
observed frequency	O_i	35	51	64	50
difference score	$O_i - E_i$	-15	1	14	0
squared difference	$(O_i - E_i)^2$	225	1	196	0
scaled sq. diff.	$(O_i - E_i)^2/E_i$	4.50	0.02	3.92	0.00

In effect, what we've got here are four different "error" scores, each one telling us how big a "mistake" the null hypothesis made when we tried to use it to predict our observed frequencies. So, in order to convert this into a useful test statistic, one thing we could do is just add these numbers up. The result is called the **goodness-of-fit** statistic, conventionally referred to either as χ^2 (chi-square) or GOF. We can calculate it as $4.50 + 0.02 + 3.92 + 0.00 = 8.44$.

If we let k refer to the total number of categories (i.e., $k = 4$ for our cards data), then the χ^2 statistic is given by:

$$\chi^2 = \sum_{i=1}^k \frac{(O_i - E_i)^2}{E_i}$$

Intuitively, it's clear that if χ^2 is small, then the observed data O_i are very close to what the null hypothesis predicted E_i , so we're going to need a large χ^2 statistic in order to reject the null.

As we've seen from our calculations, in our cards data set we've got a value of $\chi^2 = 8.44$. So now the question becomes is this a big enough value to reject the null?

1.1.4 The sampling distribution of the GOF statistic

To determine whether or not a particular value of χ^2 is large enough to justify rejecting the null hypothesis, we're going to need to figure out what the sampling distribution for χ^2 would be if the null hypothesis were true. So that's what I'm going to do in this section. I'll show you in a fair amount of detail how this sampling distribution is constructed, and then, in the next section, use it to build up a hypothesis test. If you want to cut to the chase and are willing to take it on faith that the sampling distribution is a **χ^2 (chi-square) distribution** with $k - 1$ degrees of freedom, you can skip the rest of this section. However, if you want to understand *why* the goodness-of-fit test works the way it does, read on.

Okay, let's suppose that the null hypothesis is actually true. If so, then the true probability that an observation falls in the i -th category is P_i . After all, that's pretty much the definition

of our null hypothesis. Let's think about what this actually means. This is kind of like saying that "nature" makes the decision about whether or not the observation ends up in category i by flipping a weighted coin (i.e., one where the probability of getting a head is P_i). And therefore we can think of our observed frequency O_i by imagining that nature flipped N of these coins (one for each observation in the data set), and exactly O_i of them came up heads. Obviously, this is a pretty weird way to think about the experiment. But what it does (I hope) is remind you that we've actually seen this scenario before. It's exactly the same set up that gave rise to the binomial distribution in Section ???. In other words, if the null hypothesis is true, then it follows that our observed frequencies were generated by sampling from a binomial distribution:

$$O_i \sim \text{Binomial}(P_i, N)$$

Now, if you remember from our discussion of the central limit theorem (Section ???) the binomial distribution starts to look pretty much identical to the normal distribution, especially when N is large and when P_i isn't *too* close to 0 or 1. In other words as long as $N \times P_i$ is large enough. Or, to put it another way, when the expected frequency E_i is large enough then the theoretical distribution of O_i is approximately normal. Better yet, if O_i is normally distributed, then so is $(O_i - E_i)/\sqrt{E_i}$. Since E_i is a fixed value, subtracting off E_i and dividing by $\sqrt{E_i}$ changes the mean and standard deviation of the normal distribution but that's all it does. Okay, so now let's have a look at what our goodness-of-fit statistic actually *is*. What we're doing is taking a bunch of things that are normally-distributed, squaring them, and adding them up. Wait. We've seen that before too! As we discussed in Section ???, when you take a bunch of things that have a standard normal distribution (i.e., mean 0 and standard deviation 1), square them and then add them up, the resulting quantity has a chi-square distribution. So now we know that the null hypothesis predicts that the sampling distribution of the goodness-of-fit statistic is a chi-square distribution. Cool.

There's one last detail to talk about, namely the degrees of freedom. If you remember back to Section ???, I said that if the number of things you're adding up is k , then the degrees of freedom for the resulting chi-square distribution is k . Yet, what I said at the start of this section is that the actual degrees of freedom for the chi-square goodness-of-fit test is $k - 1$. What's up with that? The answer here is that what we're supposed to be looking at is the number of genuinely *independent* things that are getting added together. And, as I'll go on to talk about in the next section, even though there are k things that we're adding only $k - 1$ of them are truly independent,

and so the degrees of freedom is actually only $k - 1$. That's the topic of the next section.^{*3}

1.1.5 Degrees of freedom

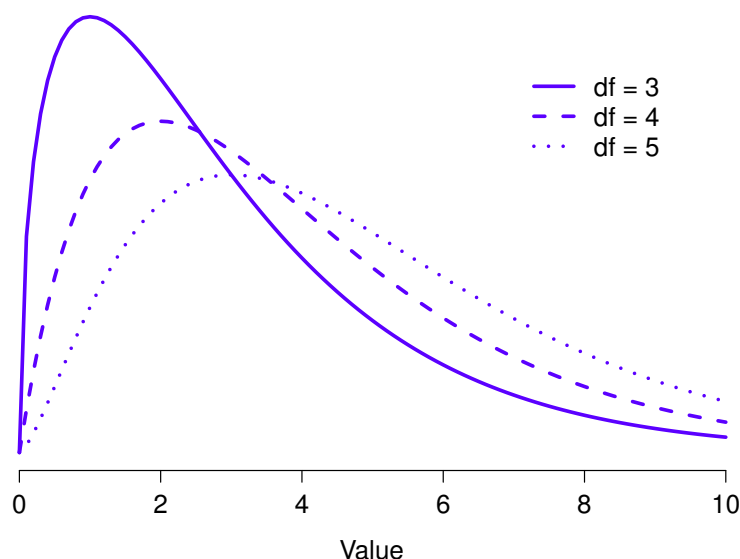


Figure 1.1 χ^2 (chi-square) distributions with different values for the “degrees of freedom”.

When I introduced the chi-square distribution in Section ??, I was a bit vague about what “degrees of freedom” actually *means*. Obviously, it matters. Looking at Figure ??, you can see that if we change the degrees of freedom then the chi-square distribution changes shape quite substantially. But what exactly *is* it? Again, when I introduced the distribution and explained its relationship to the normal distribution, I did offer an answer: it's the number of “normally distributed variables” that I'm squaring and adding together. But, for most people, that's kind of abstract and not entirely helpful. What we really need to do is try to understand degrees of freedom in terms of our data. So here goes.

The basic idea behind degrees of freedom is quite simple. You calculate it by counting up the

^{*3}If you rewrite the equation for the goodness-of-fit statistic as a sum over $k - 1$ independent things you get the “proper” sampling distribution, which is chi-square with $k - 1$ degrees of freedom. It's beyond the scope of an introductory book to show the maths in that much detail. All I wanted to do is give you a sense of why the goodness-of-fit statistic is associated with the chi-square distribution.

number of distinct “quantities” that are used to describe your data and then subtracting off all of the “constraints” that those data must satisfy.*⁴ This is a bit vague, so let’s use our cards data as a concrete example. We describe our data using four numbers, O_1 , O_2 , O_3 and O_4 corresponding to the observed frequencies of the four different categories (hearts, clubs, diamonds, spades). These four numbers are the *random outcomes* of our experiment. But my experiment actually has a fixed constraint built into it: the sample size N .^{*5} That is, if we know how many people chose hearts, how many chose diamonds and how many chose clubs, then we’d be able to figure out exactly how many chose spades. In other words, although our data are described using four numbers, they only actually correspond to $4 - 1 = 3$ degrees of freedom. A slightly different way of thinking about it is to notice that there are four *probabilities* that we’re interested in (again, corresponding to the four different categories), but these probabilities must sum to one, which imposes a constraint. Therefore the degrees of freedom is $4 - 1 = 3$. Regardless of whether you want to think about it in terms of the observed frequencies or in terms of the probabilities, the answer is the same. In general, when running the χ^2 (chi-square) goodness-of-fit test for an experiment involving k groups, then the degrees of freedom will be $k - 1$.

1.1.6 Testing the null hypothesis

The final step in the process of constructing our hypothesis test is to figure out what the rejection region is. That is, what values of χ^2 would lead us to reject the null hypothesis. As we saw earlier, large values of χ^2 imply that the null hypothesis has done a poor job of predicting the data from our experiment, whereas small values of χ^2 imply that it’s actually done pretty well. Therefore, a pretty sensible strategy would be to say there is some critical value such that if χ^2 is bigger than the critical value we reject the null, but if χ^2 is smaller than this value we retain the null. In other words, to use the language we introduced in Chapter ?? the chi-square goodness-of-fit test is always a **one-sided test**. Right, so all we have to do is figure out what this critical value is. And it’s pretty straightforward. If we want our test to have significance level of $\alpha = .05$ (that is,

*⁴I feel obliged to point out that this is an over-simplification. It works nicely for quite a few situations, but every now and then we’ll come across degrees of freedom values that aren’t whole numbers. Don’t let this worry you too much; when you come across this just remind yourself that “degrees of freedom” is actually a bit of a messy concept, and that the nice simple story that I’m telling you here isn’t the whole story. For an introductory class it’s usually best to stick to the simple story, but I figure it’s best to warn you to expect this simple story to fall apart. If I didn’t give you this warning you might start getting confused when you see $df = 3.4$ or something, (incorrectly) thinking that you had misunderstood something that I’ve taught you rather than (correctly) realising that there’s something that I haven’t told you.

*⁵In practice, the sample size isn’t always fixed. For example, we might run the experiment over a fixed period of time and the number of people participating depends on how many people show up. That doesn’t matter for the current purposes.

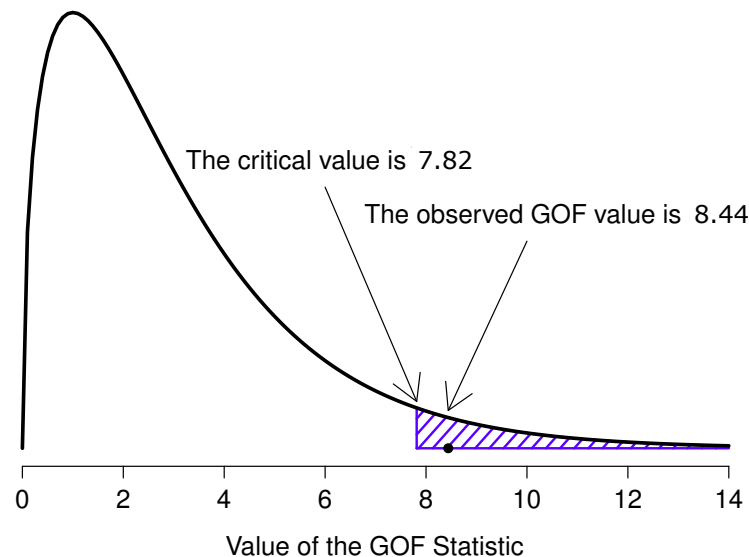


Figure1.2 Illustration of how the hypothesis testing works for the χ^2 (chi-square) goodness-of-fit test.

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we are willing to tolerate a Type I error rate of 5%), then we have to choose our critical value so that there is only a 5% chance that χ^2 could get to be that big if the null hypothesis is true. This is illustrated in Figure ??.

Ah but, I hear you ask, how do I find the critical value of a chi-square distribution with $k - 1$ degrees of freedom? Many many years ago when I first took a psychology statistics class we used to look up these critical values in a book of critical value tables, like the one in Figure ?. Looking at this Figure, we can see that the critical value for a χ^2 distribution with 3 degrees of freedom, and $p=0.05$ is 7.815.

So, if our calculated χ^2 statistic is bigger than the critical value of 7.815, then we can reject the null hypothesis (remember that the null hypothesis, H_0 , is that all four suits are chosen with equal probability). Since we actually already calculated that before (i.e., $\chi^2 = 8.44$) we can reject the null hypothesis. And that's it, basically. You now know "Pearson's χ^2 test for the goodness-of-fit".

Degrees of Freedom	Probability								
	0.95	0.90	0.70	0.50	0.30	0.10	0.05	0.01	0.001
1	0.004	0.016	0.148	0.455	1.074	2.706	3.841	6.635	10.828
2	0.103	0.211	0.713	1.386	2.408	4.605	5.991	9.210	13.816
3	0.352	0.584	1.424	2.366	3.665	6.251	7.815	11.345	16.266
4	0.711	1.064	2.195	3.357	4.878	7.779	9.488	13.277	18.467
5	1.145	1.610	3.000	4.351	6.064	9.236	11.070	15.086	20.515
6	1.635	2.204	3.828	5.348	7.231	10.645	12.592	16.812	22.458
7	2.167	2.833	4.671	6.346	8.383	12.017	14.067	18.475	24.322
8	2.733	3.490	5.527	7.344	9.524	13.362	15.507	20.090	26.124
9	3.325	4.168	6.393	8.343	10.656	14.684	16.919	21.666	27.877
10	3.940	4.865	7.267	9.342	11.781	15.987	18.307	23.209	29.588
	Non-significant						Significant		

Figure1.3 Table of critical values for the chi-square distribution

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Lucky you.

1.1.7 Doing the test in JASP

Not surprisingly, JASP provides an analysis that will do these calculations for you. From the main 'Analyses' toolbar select 'Frequencies' - 'Multinomial Test'. Then in the analysis window that appears move the variable you want to analyse ([choice_1](#) across into the 'Factor' box. Also, click on the 'Descriptives' check box so that you see the expected counts in the results table. When you have done all this, you should see the analysis results in JASP as in Figure ???. No surprise then that JASP provides the same expected counts and statistics that we calculated by hand above, with a χ^2 value of 8.44 with 3 d.f. and $p=0.038$. Note that we don't need to look up a critical p-value threshold value any more, as JASP gives us the actual p -value of the calculated χ^2 for 3 d.f.

1.1.8 Specifying a different null hypothesis

At this point you might be wondering what to do if you want to run a goodness-of-fit test but your null hypothesis is *not* that all categories are equally likely. For instance, let's suppose that someone had made the theoretical prediction that people should choose red cards 60% of the

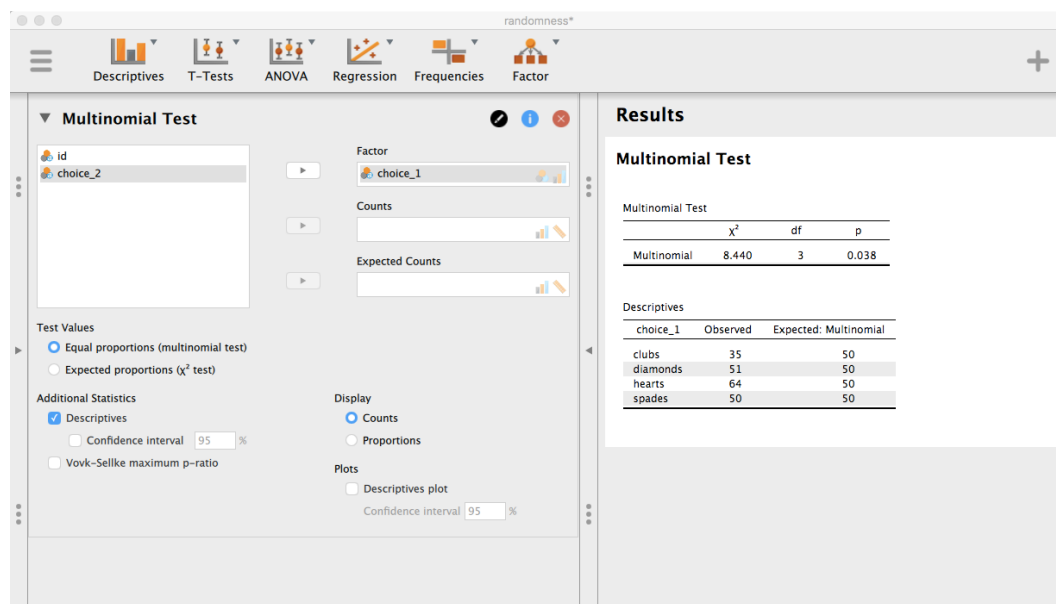


Figure1.4 A χ^2 goodness-of-fit test in JASP, with table showing both observed and expected frequencies.

time, and black cards 40% of the time (I've no idea why you'd predict that), but had no other preferences. If that were the case, the null hypothesis would be to expect 30% of the choices to be hearts, 30% to be diamonds, 20% to be spades and 20% to be clubs. In other words we would expect hearts and diamonds to each appear 60 times (30% of 200 is 60), and spades and clubs to each appear 40 times (20% of 200 is 40). This seems like a silly theory to me, but nonetheless, it's pretty easy to test this explicitly specified null hypothesis with the data in our JASP analysis. In the analysis window (see Figure ??) you can click the radio button for 'Expected Proportions (χ^2 test)'. When you do this, there are options for entering different expected counts for the variable you have selected, in our case this is `choice_1`. Change the counts to reflect the new null hypothesis, as in Figure ??, and see how the results change.

The expected counts are now:

	♣	♦	♥	♠
expected frequency E_i	40	60	60	40

and the χ^2 statistic is 4.742, 3 d.f., $p = 0.192$. Now, the results of our updated hypotheses and the expected frequencies are different from what they were last time. As a consequence our χ^2 test statistic is different, and our p -value is different too. Annoyingly, the p -value is .192, so we can't reject the null hypothesis (look back at section ?? to remind yourself why). Sadly, despite

Test Values

☐ Equal proportions (multinomial test)
☒ Expected proportions (χ^2 test)

	H_0 (a)
clubs	40
diamonds	60
hearts	60
spades	40

Figure1.5 Changing the expected proportions in the χ^2 goodness-of-fit test in JASP

the fact that the null hypothesis corresponds to a very silly theory, these data don't provide enough evidence against it.

1.1.9 How to report the results of the test

So now you know how the test works, and you know how to do the test using a wonderful JASP-flavoured magic computing box. The next thing you need to know is how to write up the results. After all, there's no point in designing and running an experiment and then analysing the data if you don't tell anyone about it! So let's now talk about what you need to do when reporting your analysis. Let's stick with our card-suits example. If I wanted to write this result up for a paper or something, then the conventional way to report this would be to write something like this:

Of the 200 participants in the experiment, 64 selected hearts for their first choice, 51 selected diamonds, 50 selected spades, and 35 selected clubs. A chi-square goodness-of-fit test was conducted to test whether the choice probabilities were identical for all four suits. The results were significant ($\chi^2(3) = 8.44, p < .05$), suggesting that people did not select suits purely at random.

This is pretty straightforward and hopefully it seems pretty unremarkable. That said, there's a few things that you should note about this description:

- *The statistical test is preceded by the descriptive statistics.* That is, I told the reader

something about what the data look like before going on to do the test. In general, this is good practice. Always remember that your reader doesn't know your data anywhere near as well as you do. So, unless you describe it to them properly, the statistical tests won't make any sense to them and they'll get frustrated and cry.

- *The description tells you what the null hypothesis being tested is.* To be honest, writers don't always do this but it's often a good idea in those situations where some ambiguity exists, or when you can't rely on your readership being intimately familiar with the statistical tools that you're using. Quite often the reader might not know (or remember) all the details of the test that you're using, so it's a kind of politeness to "remind" them! As far as the goodness-of-fit test goes, you can usually rely on a scientific audience knowing how it works (since it's covered in most intro stats classes). However, it's still a good idea to be explicit about stating the null hypothesis (briefly!) because the null hypothesis can be different depending on what you're using the test for. For instance, in the cards example my null hypothesis was that all the four suit probabilities were identical (i.e., $P_1 = P_2 = P_3 = P_4 = 0.25$), but there's nothing special about that hypothesis. I could just as easily have tested the null hypothesis that $P_1 = 0.7$ and $P_2 = P_3 = P_4 = 0.1$ using a goodness-of-fit test. So it's helpful to the reader if you explain to them what your null hypothesis was. Also, notice that I described the null hypothesis in words, not in maths. That's perfectly acceptable. You can describe it in maths if you like, but since most readers find words easier to read than symbols, most writers tend to describe the null using words if they can.
- *A "stat block" is included.* When reporting the results of the test itself, I didn't just say that the result was significant, I included a "stat block" (i.e., the dense mathematical-looking part in the parentheses) which reports all the "key" statistical information. For the chi-square goodness-of-fit test, the information that gets reported is the test statistic (that the goodness-of-fit statistic was 8.44), the information about the distribution used in the test (χ^2 with 3 degrees of freedom which is usually shortened to $\chi^2(3)$), and then the information about whether the result was significant (in this case $p < .05$). The particular information that needs to go into the stat block is different for every test, and so each time I introduce a new test I'll show you what the stat block should look like.^{*6} However the general principle is that you should always provide enough information so that the reader could check the test results themselves if they really wanted to.
- *The results are interpreted.* In addition to indicating that the result was significant, I

^{*6}Well, sort of. The conventions for how statistics should be reported tend to differ somewhat from discipline to discipline. I've tended to stick with how things are done in psychology, since that's what I do. But the general principle of providing enough information to the reader to allow them to check your results is pretty universal, I think.

provided an interpretation of the result (i.e., that people didn't choose randomly). This is also a kindness to the reader, because it tells them something about what they should believe about what's going on in your data. If you don't include something like this, it's really hard for your reader to understand what's going on.*⁷

As with everything else, your overriding concern should be that you *explain* things to your reader. Always remember that the point of reporting your results is to communicate to another human being. I cannot tell you just how many times I've seen the results section of a report or a thesis or even a scientific article that is just gibberish, because the writer has focused solely on making sure they've included all the numbers and forgotten to actually communicate with the human reader.

1.1.10 A comment on statistical notation

Satan delights equally in statistics and in quoting scripture

– H.G. Wells

If you've been reading very closely, and are as much of a mathematical pedant as I am, there is one thing about the way I wrote up the chi-square test in the last section that might be bugging you a little bit. There's something that feels a bit wrong with writing " $\chi^2(3) = 8.44$ ", you might be thinking. After all, it's the goodness-of-fit statistic that is equal to 8.44, so shouldn't I have written $X^2 = 8.44$ or maybe $GOF = 8.44$? This seems to be conflating the *sampling distribution* (i.e., χ^2 with $df = 3$) with the *test statistic* (i.e., X^2). Odds are you figured it was a typo, since χ and X look pretty similar. Oddly, it's not. Writing $\chi^2(3) = 8.44$ is essentially a highly condensed way of writing "the sampling distribution of the test statistic is $\chi^2(3)$, and the value of the test statistic is 8.44".

In one sense, this is kind of silly. There are *lots* of different test statistics out there that turn out to have a chi-square sampling distribution. The X^2 statistic that we've used for our goodness-of-fit test is only one of many (albeit one of the most commonly encountered ones). In a sensible, perfectly organised world we'd *always* have a separate name for the test statistic and

^{*7}To some people, this advice might sound odd, or at least in conflict with the "usual" advice on how to write a technical report. Very typically, students are told that the "results" section of a report is for describing the data and reporting statistical analysis, and the "discussion" section is for providing interpretation. That's true as far as it goes, but I think people often interpret it way too literally. The way I usually approach it is to provide a quick and simple interpretation of the data in the results section, so that my reader understands what the data are telling us. Then, in the discussion, I try to tell a bigger story about how my results fit with the rest of the scientific literature. In short, don't let the "interpretation goes in the discussion" advice turn your results section into incomprehensible garbage. Being understood by your reader is *much* more important.

the sampling distribution. That way, the stat block itself would tell you exactly what it was that the researcher had calculated. Sometimes this happens. For instance, the test statistic used in the Pearson goodness-of-fit test is written X^2 , but there's a closely related test known as the G -test^{*8} (Sokal1994), in which the test statistic is written as G . As it happens, the Pearson goodness-of-fit test and the G -test both test the same null hypothesis, and the sampling distribution is exactly the same (i.e., chi-square with $k - 1$ degrees of freedom). If I'd done a G -test for the cards data rather than a goodness-of-fit test, then I'd have ended up with a test statistic of $G = 8.65$, which is slightly different from the $X^2 = 8.44$ value that I got earlier and which produces a slightly smaller p -value of $p = .034$. Suppose that the convention was to report the test statistic, then the sampling distribution, and then the p -value. If that were true, then these two situations would produce different stat blocks: my original result would be written $X^2 = 8.44, \chi^2(3), p = .038$, whereas the new version using the G -test would be written as $G = 8.65, \chi^2(3), p = .034$. However, using the condensed reporting standard, the original result is written $\chi^2(3) = 8.44, p = .038$, and the new one is written $\chi^2(3) = 8.65, p = .034$, and so it's actually unclear which test I actually ran.

So why don't we live in a world in which the contents of the stat block uniquely specifies what tests were ran? The deep reason is that life is messy. We (as users of statistical tools) want it to be nice and neat and organised. We want it to be *designed*, as if it were a product, but that's not how life works. Statistics is an intellectual discipline just as much as any other one, and as such it's a massively distributed, partly-collaborative and partly-competitive project that no-one really understands completely. The things that you and I use as data analysis tools weren't created by an Act of the Gods of Statistics. They were invented by lots of different people, published as papers in academic journals, implemented, corrected and modified by lots of other people, and then explained to students in textbooks by someone else. As a consequence, there's a *lot* of test statistics that don't even have names, and as a consequence they're just given the same name as the corresponding sampling distribution. As we'll see later, any test statistic that follows a χ^2 distribution is commonly called a "chi-square statistic", anything that follows a t -distribution is called a " t -statistic", and so on. But, as the χ^2 versus G example illustrates, two different things with the same sampling distribution are still, well, different.

As a consequence, it's sometimes a good idea to be clear about what the actual test was that you ran, especially if you're doing something unusual. If you just say "chi-square test" it's not actually clear what test you're talking about. Although, since the two most common chi-square tests are the goodness-of-fit test and the independence test (Section ??), most readers with stats training can probably guess. Nevertheless, it's something to be aware of.

^{*8}Complicating matters, the G -test is a special case of a whole class of tests that are known as *likelihood ratio tests*. I don't cover LRTs in this book, but they are quite handy things to know about.

The χ^2 test of independence (or association)

GUARDBOT 1: Halt!
GUARDBOT 2: Be you robot or human?
LEELA: Robot...we be.
FRY: Uh, yup! Just two robots out robbing it up! Eh?
GUARDBOT 1: Administer the test.
GUARDBOT 2: Which of the following would you most prefer?
A: A puppy, B: A pretty flower from your sweetie,
or C: A large properly-formatted data file?
GUARDBOT 1: Choose!
– Futurama, “Fear of a Bot Planet”

The other day I was watching an animated documentary examining the quaint customs of the natives of the planet *Chapek 9*. Apparently, in order to gain access to their capital city a visitor must prove that they’re a robot, not a human. In order to determine whether or not a visitor is human, the natives ask whether the visitor prefers puppies, flowers, or large, properly formatted data files. “Pretty clever,” I thought to myself “but what if humans and robots have the same preferences? That probably wouldn’t be a very good test then, would it?” As it happens, I got my hands on the testing data that the civil authorities of *Chapek 9* used to check this. It turns out that what they did was very simple. They found a bunch of robots and a bunch of humans and asked them what they preferred. I saved their data in a file called `chapek9.csv`, which we can now load into JASP. As well as the `ID` variable that identifies individual people, there are two nominal text variables, `species` and `choice`. In total there are 180 entries in the data set, one for each person (counting both robots and humans as “people”) who was asked to make a choice. Specifically, there are 93 humans and 87 robots, and overwhelmingly the preferred choice is the data file. You can check this yourself by asking JASP for Frequency Tables, under the ‘Descriptives’ - ‘Descriptive Statistics’ button. However, this summary does not address the question we’re interested in. To do that, we need a more detailed description of the data. What we want to do is look at the `choices` broken down by `species`. That is, we need to cross-tabulate the data. In JASP we do this using the ‘Frequencies’ - ‘Contingency Tables’ button, moving `species` into the ‘Columns’ box and `choice` into the ‘Rows’ box. This procedure should produce a table similar to this:

	Robot	Human	Total
Puppy	13	15	28
Flower	30	13	43
Data	44	65	109
Total	87	93	180

From this, it's quite clear that the vast majority of the humans chose the data file, whereas the robots tended to be a lot more even in their preferences. Leaving aside the question of *why* the humans might be more likely to choose the data file for the moment (which does seem quite odd, admittedly), our first order of business is to determine if the discrepancy between human choices and robot choices in the data set is statistically significant.

1.2.1 Constructing our hypothesis test

How do we analyse this data? Specifically, since my *research* hypothesis is that “humans and robots answer the question in different ways”, how can I construct a test of the *null* hypothesis that “humans and robots answer the question the same way”? As before, we begin by establishing some notation to describe the data:

	Robot	Human	Total
Puppy	O_{11}	O_{12}	R_1
Flower	O_{21}	O_{22}	R_2
Data	O_{31}	O_{32}	R_3
Total	C_1	C_2	N

In this notation we say that O_{ij} is a count (observed frequency) of the number of respondents that are of species j (robots or human) who gave answer i (puppy, flower or data) when asked to make a choice. The total number of observations is written N , as usual. Finally, I've used R_i to denote the row totals (e.g., R_1 is the total number of people who chose the flower), and C_j to denote the column totals (e.g., C_1 is the total number of robots).^{*9}

So now let's think about what the null hypothesis says. If robots and humans are responding

^{*9}A technical note. The way I've described the test pretends that the column totals are fixed (i.e., the researcher intended to survey 87 robots and 93 humans) and the row totals are random (i.e., it just turned out that 28 people chose the puppy). To use the terminology from my mathematical statistics textbook (Hogg2005), I should technically refer to this situation as a chi-square test of homogeneity and reserve the term chi-square test of independence for the situation where both the row and column totals are random outcomes of the experiment. In the initial drafts of this book that's exactly what I did. However, it turns out that these two tests are identical, and so I've collapsed them together.

in the same way to the question, it means that the probability that “a robot says puppy” is the same as the probability that “a human says puppy”, and so on for the other two possibilities. So, if we use P_{ij} to denote “the probability that a member of species j gives response i ” then our null hypothesis is that:

$$\begin{aligned} H_0: \quad & \text{All of the following are true:} \\ & P_{11} = P_{12} \text{ (same probability of saying “puppy”),} \\ & P_{21} = P_{22} \text{ (same probability of saying “flower”), and} \\ & P_{31} = P_{32} \text{ (same probability of saying “data”).} \end{aligned}$$

And actually, since the null hypothesis is claiming that the true choice probabilities don’t depend on the species of the person making the choice, we can let P_i refer to this probability, e.g., P_1 is the true probability of choosing the puppy.

Next, in much the same way that we did with the goodness-of-fit test, what we need to do is calculate the expected frequencies. That is, for each of the observed counts O_{ij} , we need to figure out what the null hypothesis would tell us to expect. Let’s denote this expected frequency by E_{ij} . This time, it’s a little bit trickier. If there are a total of C_j people that belong to species j , and the true probability of anyone (regardless of species) choosing option i is P_i , then the expected frequency is just:

$$E_{ij} = C_j \times P_i$$

Now, this is all very well and good, but we have a problem. Unlike the situation we had with the goodness-of-fit test, the null hypothesis doesn’t actually specify a particular value for P_i . It’s something we have to estimate (Chapter ??) from the data! Fortunately, this is pretty easy to do. If 28 out of 180 people selected the flowers, then a natural estimate for the probability of choosing flowers is 28/180, which is approximately .16. If we phrase this in mathematical terms, what we’re saying is that our estimate for the probability of choosing option i is just the row total divided by the total sample size:

$$\hat{P}_i = \frac{R_i}{N}$$

Therefore, our expected frequency can be written as the product (i.e. multiplication) of the row total and the column total, divided by the total number of observations:^{*10}

$$E_{ij} = \frac{R_i \times C_j}{N}$$

^{*10}Technically, E_{ij} here is an estimate, so I should probably write it \hat{E}_{ij} . But since no-one else does, I won’t either.

Now that we've figured out how to calculate the expected frequencies, it's straightforward to define a test statistic, following the exact same strategy that we used in the goodness-of-fit test. In fact, it's pretty much the *same* statistic.

For a contingency table with r rows and c columns, the equation that defines our X^2 statistic is

$$X^2 = \sum_{i=1}^r \sum_{j=1}^c \frac{(E_{ij} - O_{ij})^2}{E_{ij}}$$

The only difference is that I have to include two summation signs (i.e., \sum) to indicate that we're summing over both rows and columns.

As before, large values of X^2 indicate that the null hypothesis provides a poor description of the data, whereas small values of X^2 suggest that it does a good job of accounting for the data. Therefore, just like last time, we want to reject the null hypothesis if X^2 is too large.

Not surprisingly, this statistic is χ^2 distributed. All we need to do is figure out how many degrees of freedom are involved, which actually isn't too hard. As I mentioned before, you can (usually) think of the degrees of freedom as being equal to the number of data points that you're analysing, minus the number of constraints. A contingency table with r rows and c columns contains a total of $r \times c$ observed frequencies, so that's the total number of observations. What about the constraints? Here, it's slightly trickier. The answer is always the same

$$df = (r - 1)(c - 1)$$

but the explanation for *why* the degrees of freedom takes this value is different depending on the experimental design. For the sake of argument, let's suppose that we had honestly intended to survey exactly 87 robots and 93 humans (column totals fixed by the experimenter), but left the row totals free to vary (row totals are random variables). Let's think about the constraints that apply here. Well, since we deliberately fixed the column totals by Act of Experimenter, we have c constraints right there. But, there's actually more to it than that. Remember how our null hypothesis had some free parameters (i.e., we had to estimate the P_i values)? Those matter too. I won't explain why in this book, but every free parameter in the null hypothesis is rather like an additional constraint. So, how many of those are there? Well, since these probabilities have to sum to 1, there's only $r - 1$ of these. So our total degrees of freedom is:

$$\begin{aligned} df &= (\text{number of observations}) - (\text{number of constraints}) \\ &= (rc) - (c + (r - 1)) \\ &= rc - c - r + 1 \\ &= (r - 1)(c - 1) \end{aligned}$$

Alternatively, suppose that the only thing that the experimenter fixed was the total sample size N .

That is, we quizzed the first 180 people that we saw and it just turned out that 87 were robots and 93 were humans. This time around our reasoning would be slightly different, but would still lead us to the same answer. Our null hypothesis still has $r - 1$ free parameters corresponding to the choice probabilities, but it now *also* has $c - 1$ free parameters corresponding to the species probabilities, because we'd also have to estimate the probability that a randomly sampled person turns out to be a robot.^{*11} Finally, since we did actually fix the total number of observations N , that's one more constraint. So, now we have rc observations, and $(c - 1) + (r - 1) + 1$ constraints. What does that give?

$$\begin{aligned} df &= (\text{number of observations}) - (\text{number of constraints}) \\ &= rc - ((c - 1) + (r - 1) + 1) \\ &= rc - c - r + 1 \\ &= (r - 1)(c - 1) \end{aligned}$$

Amazing.

1.2.2 Doing the test in JASP

Okay, now that we know how the test works let's have a look at how it's done in JASP. As tempting as it is to lead you through the tedious calculations so that you're forced to learn it the long way, I figure there's no point. I already showed you how to do it the long way for the goodness-of-fit test in the last section, and since the test of independence isn't conceptually any different, you won't learn anything new by doing it the long way. So instead I'll go straight to showing you the easy way. After you have run the test in JASP ('Frequencies' - 'Contingency Tables'), all you have to do is look underneath the contingency table in the JASP results window and there is the χ^2 statistic for you. This shows a χ^2 statistic value of 10.722, with 2 d.f. and p -value = 0.005.

That was easy, wasn't it! You can also ask JASP to show you the expected counts - just click on the check box for 'Counts' - 'Expected' in the 'Cells' options and the expected counts will appear in the contingency table. And whilst you are doing that, an effect size measure would be helpful. We'll choose Cramer's V, and you can specify this from a check box in the 'Statistics' options, and it gives a value for Cramer's V of 0.244. We will talk about this some more in just a moment.

This output gives us enough information to write up the result:

Pearson's χ^2 revealed a significant association between species and choice ($\chi^2(2) = 10.7, p < .01$). Robots appeared to be more likely to say that they prefer flowers,

^{*11}A problem many of us worry about in real life.

but the humans were more likely to say they prefer data.

Notice that, once again, I provided a little bit of interpretation to help the human reader understand what's going on with the data. Later on in my discussion section I'd provide a bit more context. To illustrate the difference, here's what I'd probably say later on:

The fact that humans appeared to have a stronger preference for raw data files than robots is somewhat counter-intuitive. However, in context it makes some sense, as the civil authority on Chapek 9 has an unfortunate tendency to kill and dissect humans when they are identified. As such it seems most likely that the human participants did not respond honestly to the question, so as to avoid potentially undesirable consequences. This should be considered to be a substantial methodological weakness.

This could be classified as a rather extreme example of a reactivity effect, I suppose. Obviously, in this case the problem is severe enough that the study is more or less worthless as a tool for understanding the difference preferences among humans and robots. However, I hope this illustrates the difference between getting a statistically significant result (our null hypothesis is rejected in favour of the alternative), and finding something of scientific value (the data tell us nothing of interest about our research hypothesis due to a big methodological flaw).

1.2.3 Postscript

I later found out the data were made up, and I'd been watching cartoons instead of doing work.

1.3

The continuity correction

Okay, time for a little bit of a digression. I've been lying to you a little bit so far. There's a tiny change that you need to make to your calculations whenever you only have 1 degree of freedom. It's called the "continuity correction", or sometimes the **Yates correction**. Remember what I pointed out earlier: the χ^2 test is based on an approximation, specifically on the assumption that the binomial distribution starts to look like a normal distribution for large N . One problem with this is that it often doesn't quite work, especially when you've only got 1 degree of freedom (e.g., when you're doing a test of independence on a 2×2 contingency table). The main reason for this is that

the true sampling distribution for the χ^2 statistic is actually discrete (because you're dealing with categorical data!) but the χ^2 distribution is continuous. This can introduce systematic problems. Specifically, when N is small and when $df = 1$, the goodness-of-fit statistic tends to be "too big", meaning that you actually have a bigger α value than you think (or, equivalently, the p values are a bit too small).

Yates1934 suggested a simple fix, in which you redefine the goodness-of-fit statistic as:

$$\chi^2 = \sum_i \frac{(|E_i - O_i| - 0.5)^2}{E_i}$$

Basically, he just subtracts off 0.5 everywhere.

As far as I can tell from reading Yates' paper, the correction is basically a hack. It's not derived from any principled theory. Rather, it's based on an examination of the behaviour of the test, and observing that the corrected version seems to work better. You can specify this correction in JASP from a check box in the 'Statistics' options, where it is called ' χ^2 continuity correction'.

1.4

Effect size

As we discussed earlier (Section ??), it's becoming commonplace to ask researchers to report some measure of effect size. So, let's suppose that you've run your chi-square test, which turns out to be significant. So you now know that there is some association between your variables (independence test) or some deviation from the specified probabilities (goodness-of-fit test). Now you want to report a measure of effect size. That is, given that there is an association or deviation, how strong is it?

There are several different measures that you can choose to report, and several different tools that you can use to calculate them. I won't discuss all of them but will instead focus on the most commonly reported measures of effect size.

By default, the two measures that people tend to report most frequently are the ϕ statistic and the somewhat superior version, known as Cramér's V .

Mathematically, they're very simple. To calculate the ϕ statistic, you just divide your X^2 value by the sample size, and take the square root:

$$\phi = \sqrt{\frac{X^2}{N}}$$

The idea here is that the ϕ statistic is supposed to range between 0 (no association at all) and 1 (perfect association), but it doesn't always do this when your contingency table is bigger than 2×2 , which is a total pain. For bigger tables it's actually possible to obtain $\phi > 1$, which is pretty unsatisfactory. So, to correct for this, people usually prefer to report the V statistic proposed by **Cramer1946**. It's a pretty simple adjustment to ϕ . If you've got a contingency table with r rows and c columns, then define $k = \min(r, c)$ to be the smaller of the two values. If so, then **Cramér's V** statistic is

$$V = \sqrt{\frac{X^2}{N(k-1)}}$$

And you're done. This seems to be a fairly popular measure, presumably because it's easy to calculate, and it gives answers that aren't completely silly. With Cramer's V , you know that the value really does range from 0 (no association at all) to 1 (perfect association).

1.5

Assumptions of the test(s)

All statistical tests make assumptions, and it's usually a good idea to check that those assumptions are met. For the chi-square tests discussed so far in this chapter, the assumptions are:

- *Expected frequencies are sufficiently large.* Remember how in the previous section we saw that the χ^2 sampling distribution emerges because the binomial distribution is pretty similar to a normal distribution? Well, like we discussed in Chapter ?? this is only true when the number of observations is sufficiently large. What that means in practice is that all of the expected frequencies need to be reasonably big. How big is reasonably big? Opinions differ, but the default assumption seems to be that you generally would like to see all your expected frequencies larger than about 5, though for larger tables you would probably be okay if at least 80% of the the expected frequencies are above 5 and none of them are below 1. However, from what I've been able to discover (**Cochran1954**) these seem to

have been proposed as rough guidelines, not hard and fast rules, and they seem to be somewhat conservative (**Larntz1978**).

- *Data are independent of one another.* One somewhat hidden assumption of the chi-square test is that you have to genuinely believe that the observations are independent. Here's what I mean. Suppose I'm interested in proportion of babies born at a particular hospital that are boys. I walk around the maternity wards and observe 20 girls and only 10 boys. Seems like a pretty convincing difference, right? But later on, it turns out that I'd actually walked into the same ward 10 times and in fact I'd only seen 2 girls and 1 boy. Not as convincing, is it? My original 30 *observations* were massively non-independent, and were only in fact equivalent to 3 independent observations. Obviously this is an extreme (and extremely silly) example, but it illustrates the basic issue. Non-independence "stuffs things up". Sometimes it causes you to falsely reject the null, as the silly hospital example illustrates, but it can go the other way too. To give a slightly less stupid example, let's consider what would happen if I'd done the cards experiment slightly differently. Instead of asking 200 people to try to imagine sampling one card at random, suppose I asked 50 people to select 4 cards. One possibility would be that *everyone* selects one heart, one club, one diamond and one spade (in keeping with the "representativeness heuristic"; Tversky & Kahneman 1974). This is highly non-random behaviour from people, but in this case I would get an observed frequency of 50 for all four suits. For this example the fact that the observations are non-independent (because the four cards that you pick will be related to each other) actually leads to the opposite effect, falsely retaining the null.

If you happen to find yourself in a situation where independence is violated, it may be possible to use the nonparametric tests, such as the McNemar test or the Cochran test. Similarly, if your expected cell counts are too small, check out the Fisher exact test. At present, JASP does not implement these tests, but check back later! For now, we'll just mention that these tests exist, but describing them is beyond the scope of this book.

1.6 ---

Summary

The key ideas discussed in this chapter are:

- The χ^2 (chi-square) goodness-of-fit test (Section ??) is used when you have a table of observed frequencies of different categories, and the null hypothesis gives you a set of

“known” probabilities to compare them to.

- The χ^2 (chi-square) test of independence (Section ??) is used when you have a contingency table (cross-tabulation) of two categorical variables. The null hypothesis is that there is no relationship or association between the variables.
- Effect size for a contingency table can be measured in several ways (Section ??). In particular we noted the Cramér’s V statistic.
- Both versions of the Pearson test rely on two assumptions: that the expected frequencies are sufficiently large, and that the observations are independent (Section ??). Various nonparametric tests can be used for certain kinds of violations of independence or count assumptions.

If you’re interested in learning more about categorical data analysis a good first choice would be **Agresti1996** which, as the title suggests, provides an *Introduction to Categorical Data Analysis*. If the introductory book isn’t enough for you (or can’t solve the problem you’re working on) you could consider **Agresti2002**, *Categorical Data Analysis*. The latter is a more advanced text, so it’s probably not wise to jump straight from this book to that one.