RESEARCH NOTE

Multiple statistical tests: Lessons from a d20 [version 2; referees: 3 approved]

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Abstract
Statistical analyses are often conducted with α = .05. When multiple statistical tests are conducted, this procedure needs to be adjusted to compensate for the otherwise inflated Type I error. In some instances in tabletop gaming, sometimes it is desired to roll a 20-sided die (or 'd20') twice and take the greater outcome. Here I draw from probability theory and the case of a d20, where the probability of obtaining any specific outcome is $1/20$, to determine the probability of obtaining a specific outcome (Type-I error) at least once across repeated, independent statistical tests.

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Introduction

In scientific research, it is important to consider the issue of conducting multiple statistical tests and the likelihood of spuriously obtaining a ‘significant’ effect. Within a null-hypothesis significance testing (NHST) framework, statistical tests are usually conducted with $\alpha = .05$, i.e., the likelihood of falsely rejecting the null hypothesis as .05. Interestingly, this value coincides with the probability of obtaining a specific outcome on a 20-sided dice (or ‘d20’), as $\frac{1}{20} = .05$. In the current (fifth) edition of Dungeons & Dragons, a tabletop game, many in-game events are determined based on the outcome of a d20. However, to make some events more likely, there are times when players roll a d20 ‘with advantage’, meaning that they roll the d20 twice and take the greater value. (There are also instances where a d20 is rolled ‘with disadvantage’, where the lesser value is taken, but here I will only focus on the former case.) This parallels the use of NHST without any correction for multiple comparisons, as it is more likely to get a significant effect due to chance (i.e., Type-I error) if many tests are conducted without a correction for multiple comparisons.

Here I wondered how much the probability of obtaining a 20, on a d20, would increase due to multiple tests—i.e., obtaining at least one 20 across n die. This approach assumes that each statistical test is wholly independent from each other, and thus is likely to over-estimate the effect related to conducting multiple statistical tests using variations in how the measures are calculated or the use of different, but correlated, measures. Nonetheless, this exploration is based in probability theory and mathematical derivations, rather than computational simulations, and can serve as a comprehensible primer in understanding the relationship between repeated statistical tests and probability distributions.

Developing an intuition of statistics and probability distributions is of particular importance as most people, both laymen and scientists, have misconceptions about NHST. This is further compounded by critics of NHST, which often over-emphasize the limitations of the approach, e.g., see 4–6. By providing a comprehensible example of how repeated statistical tests can inflate chance likelihoods, I hope that these demonstrations can improve researchers’ intuitions regarding NHST. This approach is not contrary to those suggested by the use of confidence intervals and Bayesian statistics—which have become increasingly adopted across the life sciences, from medicine to psychology—but rather to improve comprehension of the characteristics of NHST.

Mathematical derivations

The probability that of a specific outcome occurring on each on $n$ die, each with $d$ sides is:

$$P(d, n) = 1 - \left(\frac{d-1}{d}\right)^n$$

The probability of obtaining a specific outcome across $n$ rolls of a $d$-sided die are listed in Table 1.

To develop some intuition of the effect of multiple die rolls, several simple cases can be considered.

For $d = 2$, i.e., a coin, the probability of obtaining at a heads when flipping one coin ($n = 1$) is $\frac{1}{2}$. The probability of obtaining a heads twice (with two coins, $n = 2$) is $\left(\frac{1}{2}\right)^2$ or $\frac{1}{4}$. In contrast, the probability of obtaining at least one heads when flipping two coins is $\frac{3}{4}$, as there are four possible outcomes (HH, HT, TH, TT) and three of them satisfy the criteria of ‘at least one heads’ ((HH, HT, TH)) and only one outcome does not ((TT)). This can more clearly be considered as the complementary event, where the probability is $1 - \frac{1}{4}$, which resolves to $\frac{3}{4}$.

For $d = 6$, i.e., a ‘conventional’ six-sided die, the probability of obtaining any specific outcome is $\frac{1}{6}$. When considering multiple dice, it is again important to differentiate the probability of obtaining ‘obtaining the same specific outcome multiple times’, e.g., the

| $n$ | $d = 2$ | $d = 6$ | $d = 20$ | $d = 100$ | $d = 1000$ |
|-----|---------|---------|----------|-----------|------------|
| 1   | .5000   | .1667   | .0500    | .0100     | .0010      |
| 2   | .7500   | .3056   | .0975    | .0199     | .0020      |
| 3   | .8750   | .4213   | .1426    | .0297     | .0030      |
| 4   | .9375   | .5177   | .1855    | .0394     | .0040      |
| 5   | .9688   | .5981   | .2262    | .0490     | .0050      |
| 6   | .9844   | .6651   | .2649    | .0585     | .0060      |
| 7   | .9922   | .7209   | .3017    | .0679     | .0070      |
| 8   | .9961   | .7674   | .3366    | .0773     | .0080      |
| 9   | .9980   | .8062   | .3698    | .0865     | .0090      |
| 10  | .9990   | .8385   | .4013    | .0956     | .0100      |
| 20  | 1.0000  | .9739   | .6415    | .1821     | .0198      |
| 50  | 1.0000  | .9999   | .9231    | .3950     | .0488      |
| 100 | 1.0000  | 1.0000  | .9941    | .6340     | .0952      |
| 500 | 1.0000  | 1.0000  | 1.0000   | .9934     | .3936      |
| 1000| 1.0000  | 1.0000  | 1.0000   | 1.0000    | .6323      |
| 10,000| 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
probability of obtaining two sixes with two dice is $\left(\frac{1}{6}\right)^2 = \frac{1}{36}$, from the case of ‘obtaining at least one specific outcome across multiple dice’. To determine the probability of obtaining a specific outcome on any of multiple dice, the complementary event should again be considered, i.e., the probability of not obtaining that outcome on any of the die. For $n = 1$, the probability of not obtaining a specific outcome is $\frac{5}{6}$. Following from this, the probability of obtaining that specific outcome is $1 - \frac{5}{6}$ or $\frac{1}{6}$. When $n = 2$, the probability of not obtaining a six on either of the dice is $\left(\frac{5}{6}\right)^2$, which resolves to $\frac{25}{36}$. The complementary event of obtaining ‘at least one six’ is $1 - \frac{25}{36}$ or $\frac{11}{36}$. Here we can see that with two dice, the probability of obtaining at least one six (or any other specific outcome) is nearly doubled, from $\frac{1}{6}$ (i.e., $\frac{1}{6}$ with a single die).

For $d = 20$, i.e., a 20-sided die, the probability of obtaining any specific outcome is $\frac{1}{20}$ or .05. If $n = 2$ dice are rolled, the probability of obtaining at least one 20 is $\frac{19}{20}$ or .95. If $n = 10$ dice are rolled, the probability of obtaining at least one 20 is $\approx .4013$. With $n = 20$ dice, this increases further to $\approx .6415$.

We can also consider a more general problem, the probability of obtaining an outcome of $o$ or greater, on at least one of $n$ $d$-sided die:

$$P(d,n,o) = 1 - \left(\frac{o-1}{d}\right)^n$$

For instance, when rolling a six-sided die, the probability of obtaining a five or higher is $\frac{1}{2}$ (equivalent to $\frac{1}{2}$. Following from the same approach of calculating the complementary event, the probability of obtaining not obtaining any two specific outcomes across multiple dice is $1 - \left(\frac{1}{6}\right)^n$, which resolves to $\frac{25}{36}$. Figure 1 and Table 2 show the probability of obtaining at least $o$ on a $d = 20$ die, across $n$ dice.

**Table 2. Probability of obtaining at least an outcome $o$ once, across $n$ d20 die.**

| o   | n = 1 | n = 2 | n = 3 | n = 4 | n = 5 |
|-----|------|------|------|------|------|
| 1   | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| 2   | .9500 | .9775 | .9999 | 1.0000 | 1.0000 |
| 3   | .9000 | .9900 | .9999 | 1.0000 | 1.0000 |
| 4   | .8500 | .9775 | .9999 | 1.0000 | 1.0000 |
| 5   | .8000 | .9600 | .9920 | .9984 | .9997 |
| 6   | .7500 | .9375 | .9844 | .9961 | .9990 |
| 7   | .7000 | .9100 | .9730 | .9919 | .9976 |
| 8   | .6500 | .8775 | .9571 | .9850 | .9947 |
| 9   | .6000 | .8400 | .9360 | .9744 | .9898 |
| 10  | .5500 | .7975 | .9089 | .9590 | .9815 |
| 11  | .5000 | .7500 | .8750 | .9375 | .9688 |
| 12  | .4500 | .6975 | .8336 | .9085 | .9497 |
| 13  | .4000 | .6400 | .7840 | .8704 | .9222 |
| 14  | .3500 | .5775 | .7254 | .8215 | .8840 |
| 15  | .3000 | .5100 | .6570 | .7599 | .8319 |
| 16  | .2500 | .4375 | .5781 | .6836 | .7627 |
| 17  | .2000 | .3600 | .4880 | .5904 | .6723 |
| 18  | .1500 | .2775 | .3859 | .4780 | .5563 |
| 19  | .1000 | .1900 | .2710 | .3439 | .4095 |
| 20  | .0500 | .0975 | .1426 | .1855 | .2262 |

**Discussion**

While it is widely understood that multiple comparisons need to be corrected for, many would underestimate the degree of inflation in Type-I error associated with additional, uncorrected statistical tests. Critically, statistical procedures have been developed to correct for multiple comparisons (e.g., Bonferroni, Tukey’s HSD), see 9 for a detailed review. Nonetheless, the mathematical derivations presented here clearly illustrate the influence of multiple statistical tests on the likelihood of obtaining a specific outcome due to chance alone. These derivations and examples should be useful in providing a concrete example of the problem associated with uncorrected multiple comparisons and may prove useful as a pedagogical tool.

**Competing interests**

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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I would like to thank Critical Role (http://www.geekandsundry.com/shows/critical-role/) for introducing me to the concept of rolling a die ‘with advantage’.

![Figure 1. Probability (P) of obtaining at least an outcome o once, across n d20 die.](image-url)
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Open Peer Review

Current Referee Status: ✓ ✓ ✓

Version 2

Referee Report 07 September 2016

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I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Competing Interests: No competing interests were disclosed.

Version 1

Referee Report 05 July 2016

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The author provides an excellent foundation for developing an intuitive understanding of null hypothesis significant testing. The concept of using a 20 sided die to assist graduate students and new researchers to better understand what exactly is meant by .05 and how multiple comparisons have a dramatic influence on interpretation is an interesting one — and I believe novel. This intuitive approach can also be used to improve understanding for the general public and overall science communication. Although this report includes a mathematical derivation, which may be too advanced for new scholars or science communication, it provides an excellent rationale for the use of 20 sided die.

When can also easily imagine that this rationale can be used better understand robustness of the outcomes of studies that may be influenced by experiment-wise error rates, such as in the cases of multiple attempts at replication or multiple trials of a specific experiment. The 20 sided die provides a concrete and real world method of communicating the complexities of multiple comparisons that is far more user-friendly than random number generators and variations of Monte Carlo studies.

I am curious as to whether the exactitude in engineering and manufacturing a 20 sided die will result in exactly equal probability of each number appearing. A six sided die is created with right angles and is relatively easy to create an equal probability of landing on each side. Obviously, this makes no difference
or changes the point of the paper; yet, it may add error should anyone actually attempt to roll the 20 sided dice multiple times. Just a thought as I am unsure on this issue. I suppose should a 20 sided die found to contain significant error or even bias, then there would be scandal in the Dungeons & Dragons world.

The author also deserves credit for establishing high levels of nerd credibility. When Dungeons & Dragons, mathematical derivations, and useful statistical communication methods are combined into a single published scientific paper; the trifecta of nerd credibility has been achieved.

Overall, this is a well-written report and the mathematics is correct. I am hopeful that the author continues to elaborate on this concept and develops other uses of a 20 sided die for communication and lesson plans in courses on research design and basic applied statistics. This will also be helpful in explaining experiment wise error rate/multiple comparisons in the cases of science communication as well.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

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Referee Report 03 June 2016

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The author provides a novel demonstration of the increasing probability of spurious research results when performing multiple tests: noticing the equivalence of a p = .05 statistical threshold and a d20 die (as used in popular games), the author goes on to describe changes in probabilities when using multiple dice, or when allowing multiple sides of the die to count as a correct result. The aim of this article, as I understand it, is to demonstrate that these changes have a surprisingly large influence on statistical hypothesis testing, and at the same time to provide a hands-on example that many readers might be able to relate to (in the form of the d20 die).

The article is well-written and in my opinion fulfills both of these goals. Its rationale and the mathematical derivations seem to be sound and correct. I can easily see this article being used by educators to teach the topic of spurious statistical results and to make the topic more accessible.

I have some minor edits/recommendations to increase the overall clarity and readability of the article:

- When the game name "Dungeons & Dragons" is first mentioned in the introduction, it should be followed by a citation of the game's publisher, year of publication, and, if necessary/appropriate, copyright information.

- A d6 die is described as "regular" in the text. This term seems ambiguous to me and I recommend replacing it with a term such as "cube-shaped," "classical," or "conventional."

- The current version of the manuscript appears to contain a printing error: before the last paragraph of the "mathematical derivations" section, the sentence fragment "across n die." is printed without context.

I recommend the indexing of this article after these minor issues have been addressed, and I hope the author will continue to produce research notes that highlight statistical issues in an approachable manner.

I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

**Competing Interests:** No competing interests were disclosed.