

## On the (ab)use of statistics in the legal case against the nurse Lucia de B.

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We discuss the statistics involved in the legal case of the nurse Lucia de B. in the Netherlands, 2003–2004. Lucia de B. witnessed an unusually high number of incidents during her shifts, and the question arose as to whether this could be attributed to chance. We discuss and criticize the statistical analysis of Henk Elffers, a statistician who was asked by the prosecutor to write a statistical report on the issue. We discuss several other possibilities for statistical analysis. Our main point is that several statistical models exist, leading to very different predictions or perhaps different answers to different questions. There is no such thing as a ‘best’ statistical analysis.

**Keywords:** statistical analysis; legal case; likelihood method; conditioning; Bayesian approach; subjective choices; roster data.

### 1. Introduction: the case

In The Hague (the Netherlands), on 24 March 2003, the nurse Lucia de B. (hereafter called either ‘Lucia’ or ‘the suspect’) was sentenced to life imprisonment for allegedly killing or attempting to kill a number of patients in two hospitals where she had worked in the recent past: the *Juliana Kinderziekenhuis* (JKZ) and the *Rode Kruis Ziekenhuis* (RKZ). At the RKZ, she worked in two different wards, numbered 41 and 42, respectively. At the JKZ, an unusually high proportion of incidents occurred during her shifts,<sup>1</sup> and the question arose as to whether Lucia’s presence at so many incidents could have been merely coincidental.

A statistical analysis was given by the statistician Henk Elffers, who had looked into the matter at the request of the public prosecutor. In broadest terms, his conclusion was the following: assuming

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<sup>1</sup> The precise technical definition of ‘incident’ is not important here; it suffices to say that an incident refers to the necessity for reanimation, regardless of the outcome of the reanimation.

only (as he says) that

1. the probability that the suspect experiences an incident during a shift is the same as the corresponding probability for any other nurse and
2. the occurrences of incidents are independent for different shifts,

then the probability that the suspect has experienced as many incidents as she in fact has is less than 1 in 342 million. According to Elffers, this probability is so small that standard statistical methodology sanctions rejection of the null hypothesis of chance. He did take care to note that in itself this does not mean the suspect is guilty.

Why do we write this article? Two of us (MvL and RM) became involved in the case as expert witnesses of the defence. We studied the method and conclusion of Elffers, and came to the conclusion that his numbers did not mean very much, if anything at all. Elffers (and the court for that matter) completely overlooked the subjective element in the choice of a probabilistic model and therefore the possibility of there being several models with very different predictions or perhaps different answers to different questions.

The question as to how to use statistics in a case like this is not a question with a well-defined answer. Borrowing a phrase of Thomas Kuhn, we deal here with a *problem* rather than a *puzzle*. There are many ways of doing statistics. One can argue whether to use a (subjective) Bayesian approach or a classical frequentist approach. There is even a school called the likelihood approach which says that you should compute and report likelihood ratios, full stop. Within each school, there can be many solutions to what appears to be the same problem. Moreover, there is the question of the range of the model.

Hence, many different approaches are possible, using very different models and with many different levels of sophistication. One can choose a very simple model, as Elffers did, giving precise results albeit of limited relevance. One can also choose a much broader perspective, like a Bayesian point of view, which involves much more data, but whose conclusions are much less precise. There simply is no unique best way of dealing with the problem, and in this paper, we want to elaborate on this point significantly. In court, the judges continued to ask us ‘so if you reject Elffers’ numbers, why don’t you give us better numbers’, implicitly assuming that there exists something like best numbers. One of the points of the present article is to argue against this.

This article is structured as follows: We will first present the relevant data and the statistical methodology used by Elffers. We discuss and criticize this methodology on several levels: not only do we offer a critical discussion of his overall approach but also we think that within his paradigm, Elffers made several important mistakes. We also briefly discuss the way the court interpreted Elffers’ report. Then, we show how the method of Elffers could have been used in a way we believe is correct within his chosen paradigm, leading to a very different conclusion. After that, we discuss a Bayesian point of view, as advocated by the Dutch econometrician de Vos, and then we move on to the so-called epidemiological models inspired by recent work of Lucy and Aitken. In Section 9, we try to formulate some conclusions.

## 2. The data and Elffers’ method

Elffers tried to base his model entirely on data pertaining to shifts of Lucia and the other nurses and the incidents occurring in those shifts. The data on shifts and incidents for the period which was singled out in Elffers’ report are given in the following table.

Hospital name (and ward number)	JKZ	RKZ-41	RKZ-42
Total number of shifts	1029	336	339
Lucia's number of shifts	142	1	58
Total number of incidents	8	5	14
Number of incidents during Lucia's shifts	8	1	5

Later, it was discovered that Lucia actually had done three shifts in RKZ-41 instead of just one, and in our own computations later in this article, we will use this correct number.

When trying to put the situation sketched into a statistical model, one's first choice might be to build a model on the basis of epidemiological data concerning the probability of incidents during various types of shifts; this would allow one to calculate the probability that the suspect would be present accidentally at as many incidents as she in fact witnessed.

However, the trouble with this approach is that for the most part, the requisite data are lacking. And even if the data were available, their use would be a subject of debate between prosecutor and defence; see Section 7.

Because of this, Elffers tried to set up a model which uses only the shift data given above. This he achieved by *conditioning* on part of the data. He assumed that

1. there is a fixed probability  $p$  for the occurrence of an incident during a shift (hence,  $p$  does not depend on whether the shift is a day shift or a night shift, etc.) and
2. incidents occur independently of each other.

It is now straightforward to compute the *conditional* probability of the event that (at the JKZ, say) all incidents occur during Lucia's shifts, *given* the total number of incidents and the total number of shifts *in the period under study*. Indeed, if the total number of shifts is  $n$  and Lucia had  $r$  shifts, then the conditional probability that Lucia witnessed  $x$  incidents given that  $k$  incidents occurred is

$$\frac{\binom{r}{x} p^x (1-p)^{r-x} \binom{n-r}{k-x} p^{k-x} (1-p)^{n-r-k+x}}{\binom{n}{k} p^k (1-p)^{n-k}} = \frac{\binom{r}{x} \binom{n-r}{k-x}}{\binom{n}{k}}. \quad (1)$$

Note that this quantity does not depend on the unknown parameter  $p$ . This distribution is known as the *hypergeometric* distribution. With this formula, one can easily compute the (conditional) probability that the suspect witnessed at least the number of incidents as she actually has, for each ward.

However, according to Elffers, this computation is not completely fair to the suspect. Indeed, the computation is being done precisely because there were so many incidents during her shifts at the JKZ. It would, therefore, be more reasonable (according to Elffers) not to compute the probability that Lucia has witnessed so many incidents but instead the probability that *some* nurse witnessed so many incidents. At the JKZ, there were 27 nurses taking care of the shifts and therefore, presumably to get an upper bound to this probability, Elffers multiplies his outcome by 27; he calls this the *post hoc correction*. According to Elffers, this correction only needs to be done at the JKZ; at the RKZ, this is no longer necessary since the suspect was already identified as being suspect on the basis of the JKZ data.

Elffers arrives at his final figure (the aforementioned 1 in 342 million) by multiplying the outcomes for the three wards (with *post hoc* correction at the JKZ, but without this correction at the RKZ).

### 3. Discussion of Elffers' method

There are a number of problems and points of concern with the method of Elffers. In the following, we list some of these.

#### 3.1 *Conditioning on part of the data*

As we remarked already, conditioning on the number of incidents has a big advantage, namely, that under the hypothesis of chance, the unknown parameter  $p$  cancels in the computations. It is the very conditioning that makes computations possible in Elffers' model.

The idea of conditioning at inference time on quantities that were not naturally fixed at data sampling time has some history. It seems that Fisher (1925) first proposed this idea for exact inference on a  $2 \times 2$  contingency table. In Mehta & Patel (1997), some justification is offered for this technique. Conditioning is reasonable, according to Mehta and Patel, if 'the margins [...] are representative of nuisance parameters whose values do not provide any information about the null-hypothesis of interest'. (They mean information about the truth or falsity of the hypothesis.) When we discuss loss of information by conditioning, the generally accepted attitude is that the loss is usually not worth fussing about. However, we deal here with a legal case, and the fact that *usually* the information loss might be not worth fussing about is not enough to dismiss this issue in an individual legal case. It is also usually the case that DNA material on the body of a crime victim comes from the criminal, but in each individual case, this needs to be confirmed.

In the current case, it is not clear at all that the number of incidents does not provide information. We do not know for sure that *any* murders were committed; all other evidences were circumstantial. If the total number of incidents happened to be smaller than normally would be expected, it becomes less plausible that many attempted murders have taken place.

#### 3.2 *Using data twice: the post hoc correction*

One of the problems with this approach is the fact that the data of the JKZ are used twice. First to identify the suspect and indeed to suspect that a crime has occurred and after that again in the computations of Elffers' probabilities. This procedure should raise eyebrows among statisticians. It is one of these problems that seems to arise all over the place: one sets up an hypothesis on the basis of certain data, and after that one uses the same data to test this hypothesis. It is clear that this raises problems, and it is equally clear that Elffers' method shares this problem. In a way, Elffers seems to be aware of this. After all, his *post hoc* correction was introduced for exactly this reason.

However, this *post hoc* correction is a striking instance of an unacknowledged subjective choice employed by Elffers. To see this, note that Elffers restricts the statistical analysis to the wards at which the suspect worked. Why? The question of the prosecutor, whether Lucia's number of incidents can be put down to chance, has to do with the question whether or not Lucia killed or attempted

to kill some of her patients. The word ‘ward’ is not mentioned in these questions nor is there any mention of the other nurses who worked there. It was the choice of Elffers himself to consider the level of wards. We do not claim that this decision was wrong; there are arguments to defend it, the most important one probably being the simplicity of the resulting model. But one can also envision a statistical analysis of all wards in, say, the Netherlands, perhaps with different probabilities for incidents in different wards. We might now condition on the number of incidents in each ward. Again, the number of incidents of the suspect has the same hypergeometric distribution as before. But the necessary *post hoc* correction in this hypothetical statistical analysis would logically take account of all nurses in the Netherlands, even though the computations concerning the suspect might still only depend on the data of her own ward. Multiplication by the number of nurses in the ward of Lucia does not necessarily follow from the fact that we only use data from her own ward; the level of the *post hoc* correction is arbitrary.

An analogy might clarify this point. Consider a lottery with tickets numbered 1 to 1 000 000. The jackpot falls on the ticket with number 223 478, and the ticket has been bought by John Smith. John Smith lives in the Da Costastraat in the city of Leiden. Given these facts, we may compute the chance that John Smith wins the jackpot; a simple and uncontroversial model shows that this probability will be extremely small. Do we conclude from this that the lottery was not fair since an event with very small probability has happened? Of course not. We can also compute the probability that someone in the Da Costastraat wins the jackpot, but it should be clear that the choice of the Da Costastraat as reference point is completely arbitrary. We might similarly compute the probability that someone in Leiden wins the jackpot or someone living in Zuid-Holland (the state in which Leiden is situated). With these data-dependent hypotheses, there simply is no uniquely defined scale of the model at which the problem must be studied.

The analogy with the case of Lucia will be clear: the winner of the jackpot represents the suspect being present at eight out of eight incidents, the street represents the ward. Elffers restricts his model to the ward in which something unusual has happened. With perhaps equal justification, another statistician might have considered the entire JKZ (Leiden, in the analogy) instead of the ward as a basis for her computations—with vastly higher probability for the relevant event to happen somewhere. Still another statistician might have taken the Netherlands as the basis for the computation, which yields again a higher probability. The important point to note is that *subjective choices are unavoidable here*, and it is rather doubtful whether a court’s judgement should be based on such choices. If one wants to avoid this kind of subjective choice, one should adopt an approach where the data are not used twice. In Section 3.3, we discuss such an approach.

Even if we agree with the level (wards) of the *post hoc* correction, the way it is done needs to be motivated. Elffers’ motivation is to compute (though presumably, he means to bound) the probability that some nurse among the 27 at JKZ would experience as many incidents as Lucia. A glance at the numbers shows that the 27 nurses must have had very varied numbers of shifts. The chance that any particular nurse would experience at least 14 incidents will depend on her total number of shifts and appears hardly relevant. More relevant would perhaps be each nurse’s incident rate or risk (average number of incidents per shift), but we are not given the numbers of shifts of the other nurses.

If we suspected *a priori* that murders had taken place at the JKZ and wanted to investigate whether they were associated with one of the nurses, then *before seeing the data* a statistician *might* reasonably adopt the following standard (Bonferroni) procedure for the so-called *multiple comparisons*: compute for each nurse separately the probability of their witnessing at least the number

of incidents which they did witness, under the hypothesis of randomness. Multiply the smallest of these probabilities by the number of nurses. The result would be a legitimate  $p$ -value (the meaning of ' $p$ -value' is discussed in Section 3.3). Thus, Elffers' *post hoc* correction *could* have been appropriate under a rather different unfolding of the events. But this does not justify his correction in the present circumstances.

Other commentators have derived Elffers' *post hoc* correction in a Bayesian approach, where it is assumed that there have been murders by a nurse and that each nurse has an equal probability of being the murderer. Again, this picture simply does not apply to the actual circumstances of the case.

### 3.3 *Multiplication is not allowed*

Elffers multiplies the three probabilities from the three wards. The multiplication means that he is assuming that under his null hypothesis, incidents occur completely randomly in each of the three wards (as far as the allocation of shifts to nurses is concerned), independently over the wards, but with possibly different rates in each ward. If one accepts his earlier null hypothesis as an interesting hypothesis to investigate, then this new hypothesis could also be of interest.

What is the meaning of the probability which Elffers finds? It is the probability, under this null hypothesis of randomness and conditional on the total number of incidents in each ward, that a nurse with as many shifts as Lucia in each ward separately would experience as many (or more) incidents than she did, in all wards simultaneously. Is the fact that this probability is very small a good reason to discredit the null hypothesis?

First, we should understand the rationale of Elffers' method when applied to one ward. He is interested to see if a certain null hypothesis is tenable (whether his null hypothesis is relevant to the case at hand is discussed in Section 3.4). He chooses in advance for whatever reason he likes a statistic (a function of the data) such that large values of that statistic would tend to occur more easily if there actually is an interesting deviation from the null hypothesis, for him. Since his null hypothesis completely fixes the distribution of his chosen statistic, he can compute the probability that the actually observed value could be equalled or exceeded under that hypothesis. The resulting probability is called the  $p$ -value of the statistical test. If null hypothesis and statistic are specified in advance of inspecting the data, then it becomes hard to retain belief in the null hypothesis if the  $p$ -value is very small. Elffers in fact follows the following procedure: he has selected (arbitrarily) a rather small threshold,  $p = 0.001$ . When a  $p$ -value is smaller than 0.001, he will declare that the null hypothesis is not true. Following this procedure, and in those cases when actually the null hypothesis was true, he will make a false declaration once in a thousand times.

If the null hypothesis corresponds to a person being innocent of having committed a crime, then his procedure carries the guarantee that not more than one in a thousand innocent persons is falsely found guilty. (Presumably, society does accept some small rate of false convictions since absolute certainty about guilt or innocence is an impossibility. But perhaps one in a thousand is a bit too large risk to take.)

Now, we return to Elffers' multiplication of three  $p$ -values, one for each ward. Does this result in a new  $p$ -value?

An easy argument shows that the answer is *no*. Suppose there are 100 wards and the null hypothesis is true (including the independence over the wards). A nurse with the same number of shifts as Lucia in each ward has approximately a probability of a half to have as many incidents as Lucia,



in each ward separately. Multiplying, the probability that she ‘beats’ Lucia in all wards is approximately 1 in 2 to the power one hundred or approximately one in a million million million million. Yet we are assuming the complete randomness of incidents within each ward. Clearly, we have to somehow discount the number of multiplications we are doing.

Is there something else that Elffers could have done to combine the results of the three wards? Yes, and in fact, classical statistics offers many choices. For instance, he could have compared the total number of incidents of Lucia over the three wards to the probability of exceeding that number, given the totals per ward and the numbers of shifts, when in each ward separately incidents are assigned uniformly at random over all the shifts. In the language of statistical hypothesis testing, he should have chosen a single test statistic based on the combined data for his combined null hypothesis and computed its  $p$ -value under that null hypothesis. Perhaps, it would be reasonable to weight the different wards in some way. Each choice gives a different test statistic and a different result. The choice should be made in advance of looking at the data, and should be designed to react to the kind of deviation from the null hypothesis which is most important to detect. Such a choice can be scientifically motivated but it is in the last analysis subjective.

An easy way to combine (under the null hypothesis) independent  $p$ -values is a method due to Fisher (1925): multiply (as Elffers did) the three  $p$ -values for the separate tests (denoted by  $p_1$ ,  $p_2$  and  $p_3$ ) and compare this with the probability distribution of the product of the same number of uniform random numbers between 0 and 1. A standard argument from probability theory reduces this to a comparison of  $-2 \sum_i \log p_i$  with a chi-squared distribution with  $2n$  degrees of freedom, where  $n = 3$ . What is in favour of this method is its simplicity. Choosing this one is just as much a subjective choice as any other. The final  $p$ -value will be much larger than that reported by Elffers.

### 3.4 *The Quine–Duhem problem*

In fact, the talk of ‘the rejection of the null hypothesis’ is somewhat imprecise. It was observed by the philosopher Quine, and before him by the historian of science Duhem, that the falsificationist picture of an hypothesis  $H$  logically implying a prediction  $P$ , which when falsified must lead to the abandonment of  $H$ , is too simplistic.

Consider the following example: suppose our thermodynamic theory implies that water boils at 100°C at sea level, and suppose furthermore that our observations show water to boil at 120°C. Does this mean thermodynamics is false? Not necessarily, because there might be something wrong with the thermometer used. That is, the logical structure of the prediction is rather

‘Thermodynamics + Properties of thermometer’ implies ‘water boils at 100°C at sea level’.

More formally, a prediction  $P$  from an hypothesis  $H$  always has the form  $H \& A_1 \& \dots \& A_n \Rightarrow P$ , where the  $A_1 \& \dots \& A_n$  are the auxiliary hypotheses. If we find that  $P$  is false, we can conclude only not- $(H \& A_1 \& \dots \& A_n)$  from which something can be concluded about  $H$  only if we have independent corroboration of the  $A_1 \& \dots \& A_n$ . The same phenomenon occurs in statistics and, in particular, in this case.

In order to be able to make calculations, Elffers in fact explicitly makes auxiliary assumptions far beyond the hypothesis of interest. In order for his conclusion to be relevant to the case, we must

make the following auxiliary assumptions:

- the probability of an incident during a night shift is the same as during a day shift (but more people die during the night);
- the probability of an incident during a shift does not depend on the prevailing atmospheric conditions (but they may have an effect on respiratory problems);
- the case mix at the ward did not systematically change over the time period concerned;
- the occurrence of an incident in shift  $n + 1$  is independent of the occurrence of an incident in shift  $n$  (however, a successful reanimation in shift  $n$  may be followed by death in shift  $n + 1$ );
- in normal circumstances, all nurses have equal probability to witness incidents (on the contrary, as our own informal enquiries in hospitals have shown, terminally ill patients often die in the presence of a nurse with whom they feel ‘comfortable’).

This is just a small sample of the auxiliary hypotheses which are needed to make the rejection of Elffers’ null hypothesis relevant to the case at hand. The main point is the following: only if the auxiliary hypotheses used in setting up the model are realistic, can the occurrence of an improbable outcome be used to cast doubt on the null hypothesis of interest. In the absence of such independent verification of the auxiliary hypotheses, the occurrence of an improbable outcome might as well point to incorrect auxiliary hypotheses.

To put it a different way, Elffers’ explicit model assumptions show how he chose to formally interpret the question asked by the court: could so many incidents occur during Lucia’s shifts by chance? Our first three items listed above suggest that the chance of an incident might vary strongly over the shifts without there being any difference between the nurses. Then, if Lucia for whatever reason tended to be assigned many more ‘heavy’ shifts than the other nurses, she will experience by chance much more than the average number of incidents. The assignment of nurses to shifts was certainly not done completely at random. Note that at the JKZ, Lucia had a much larger proportion of shifts than the other nurses. The nurses are not all the same in this respect.

Finally, as our last item shows, there may be completely innocent reasons why the chance of an incident in a particular shift might depend on the nurse who is on duty.

#### 4. The court’s interpretation of Elffers’ numbers

In its judgement of 24 March 2003, the court glossed Elffers’ findings as follows (the numbering corresponds to the court’s report; the emphasis—*italic script*—is ours):<sup>2</sup>

7. In his report of May 29, 2002, Dr H. Elffers concludes that the *probability* that a nurse *coincidentally* experiences as many incidents as the suspect is less than 1 over 342 million.

8. In his report of May 29, 2002, Dr H. Elffers has further calculated the following component probabilities:

- a. The *probability* that one out of 27 nurses would *coincidentally* experience 8 incidents in 142 out of a total of 1029 shifts ... is less than 1 over 300,000.

<sup>2</sup> The original Dutch version can be found at [www.rechtspraak.nl](http://www.rechtspraak.nl).



b. The *probability* that the suspect has *coincidentally* . . .

11. The court is of the opinion that the probabilistic calculations given by Dr H. Elffers in his report of May 29, 2002, entail that it must be considered *extremely improbable* that the suspect experienced all incidents mentioned in the indictment *coincidentally*. These calculations *consequently show* that it is *highly probable* that there is a *connection between the presence of the suspect and the occurrence of an incident*.

We have cited these excerpts from the court's judgement because the italicized phrases should raise eyebrows among statisticians. The judgement of the court is ambivalent, and it is unclear whether or not the court makes the famous mistake known as the *prosecutor's fallacy*. Clearly, one *should* talk about the probability that something happened, under the assumption that everything was totally random. The judgement of the court could, however, also be interpreted as the probability that something accidentally happened. This is quite different as it is easily illustrated with the following formal translation into mathematical language.

Writing  $E$  for the observed event and  $H_0$  for the hypothesis of chance, Elffers calculated  $P(E | H_0) < 342 \times 10^{-6}$ , while the court seems to have concluded that  $P(H_0 | E) < 342 \times 10^{-6}$ . Writing

$$P(H_0 | E) = \frac{P(E | H_0) \cdot P(H_0)}{P(E)},$$

we see that prior information about  $P(H_0)$  and  $P(E)$  would required to come to such a conclusion.

We would like to note that Elffers did not make this mistake himself, but during the testimony of two of the authors of this article (RM and MvL), the court of appeal certainly did.

## 5. Elffers' method revised

There is a simple way to revise Elffers' method in a way that avoids the scale problems and the double use of data: discard the data from JKZ and just analyse the data from the two wards at RKZ, combining the results in a statistically correct fashion.

It was the concentration of incidents during Lucia's shifts at JKZ which suggested criminal activity with herself as suspect. Elffers' analysis of those numbers informally confirms that the concentration was surprising and justifies the further investigation that took place. But the probability he reported to the court for the JKZ is misleading, if not meaningless. This does not mean that no evidence from the JKZ can be used in court; it just means that these particular data from the JKZ cannot be used in a *statistical fashion*, at least not within the classical frequentist paradigm. Data from the JKZ, for instance toxicological reports, can be used in court in different ways.

Doing similar computations as Elffers, but now restricted to the RKZ and without any correction, we obtain very different numbers. If we first take the data of the two wards together, then we have a total number of 675 shifts, Lucia having 61 of them (note the correction of numbers). There were 19 incidents, six of which were during one of Lucia's shifts. Under the same hypothesis as Elffers, a similar computation now leads to a probability of 0.0038, which of course is much larger than the number obtained by Elffers. In particular, Elffers himself used a significance level of 0.001, meaning that in this case the null hypothesis should *not* be rejected, in sharp contrast to Elffers' conclusion.

However, one should make a distinction between the two wards, which took rather different kinds of patients, and indeed the rate of incidents in each seems quite different; Lucia has proportionately more shifts in the ward where incidents are more frequent. There are several ways of taking account of this. One can combine two separate  $p$ -values as in Section 3.3, or, alternatively, treat both wards independently with the hypergeometric method as Elffers, and ask for the probability that the sum of two independent hypergeometric random variables (with their respective parameters) exceeds 6. A simple computation leads to the conclusion that this probability is equal to 0.022, still bigger than the previously found 0.0038.

It is clear that some of the aforementioned problems remain in this revised form of the method. Nevertheless, we believe that the revised form is an improvement since there is no double use of data, hence no need of a *post hoc* correction without rationale. There are still subjective choices to be made (how to combine the data from the two wards at RKZ) but this is a matter of taste, not controversy. The revised analysis shows that the data from RKZ give independent though rather weak confirmation that the rate of incidents was larger in Lucia's shifts than in those of other nurses. This does not imply that her presence is the cause. Without any information about the expected rate of incidents, about how it might vary over different kinds of shifts and about how nurses are assigned to different shifts, the data are rather inconclusive.

## 6. A Bayesian approach to the problem

During and after the trial, a public debate arose in the Netherlands about the way statistics was used in this case. Apart from Henk Elffers and two of the authors of this article, also Aart de Vos, an econometrician, entered the discussion. de Vos (*A primer in Bayesian inference, Informative priors and empirical Bayesian inference*) claimed that a Bayesian approach would solve scale problems and problems of *post hoc* data analysis. In a national newspaper, he came to the conclusion that Lucia was *not* guilty with probability at least 10%, a number in sharp contrast with Elffers' outcomes. We summarize his method here without going into details.

A Bayesian analysis works as follows: let  $E$  denote the evidence at hand,  $H_d$  the null hypothesis (the hypothesis that Lucia is innocent) and  $H_p$  denote the alternative hypothesis (the hypothesis that Lucia is guilty).

A straightforward application of Bayes' rule now gives

$$\frac{P(H_p|E)}{P(H_d|E)} = \frac{P(E|H_p)}{P(E|H_d)} \cdot \frac{P(H_p)}{P(H_d)}.$$

In (other) words,

$$\text{posterior odds} = \text{LR} \cdot \text{prior odds}.$$

We interpret  $P(H_d|E)$  as the probability of  $H_d$  after evaluating the evidence  $E$ . The posterior odds are—at least in theory—nice to work with because any new evidence ( $E_{\text{new}}$ ) can be implemented to give new posterior odds. For example, suppose we first had

$$\text{'old' posterior odds} = \frac{P(E|H_p)}{P(E|H_d)} \cdot \frac{P(H_p)}{P(H_d)},$$

then, after this new evidence, we get new posterior odds

$$\begin{aligned}\frac{P(H_p|E, E_{\text{new}})}{P(H_d|E, E_{\text{new}})} &= \frac{P(E_{\text{new}} \cap E|H_p)}{P(E_{\text{new}} \cap E|H_d)} \cdot \frac{P(H_p)}{P(H_d)} \\ &= \frac{P(E_{\text{new}}|H_p, E)}{P(E_{\text{new}}|H_d, E)} \cdot \text{old posterior odds}.\end{aligned}$$

This is all nice in theory, but the questions that arise once you try to use this in a law suit are obvious: can we make sense of  $P(H_p)$  and  $P(H_d)$ ? For what kind of evidence it is possible to compute  $P(E|H_p)/P(E|H_d)$ ? And can we make sense of  $P(E_{\text{new}}|H_p, E)/P(E_{\text{new}}|H_d, E)$ ? The latter question is particularly challenging because it is difficult to see how the different pieces of evidence are related.

In the case at hand, the following facts were brought up by de Vos as relevant evidence. After each piece of evidence, we write between parentheses the likelihood ratio for that piece of evidence as used by de Vos.

1.  $E_1$ , the fact that the suspect never confessed ( $\frac{1}{2}$ );
2.  $E_2$ , the fact that two of the patients had certain toxic substances in their blood (50);
3.  $E_3$ , the fact that 14 incidents occurred during Lucia's shifts (7000);
4.  $E_4$ , the fact that suspect had written in her diary that 'she had given in to her compulsion' (5).

It seems obvious to us that these facts are hardly, if at all, expressible as numbers; the numbers of de Vos can hardly be justified. The prior probability  $P(H_p)$  is taken to be  $10^{-5}$ , and then finally, de Vos assumes independence between the various facts, ending up with posterior odds equal to roughly 8.75. This means that the suspect is guilty with probability close to 90%, certainly not enough to convict anybody.

## 6.1 Discussion

The numbers obtained by de Vos are in sharp contrast with Elffers' outcomes. However, it is clear from the analysis that his priors and likelihood ratios are very subjective. Any change in his priors would lead to very different answers.

An advantage of the Bayesian approach is that there are no worries with *post hoc* corrections or scale problems: the priors should take care of these. Moreover, there are some constructive ideas in the modelling assumptions of de Vos; for instance, in order to arrive at a likelihood ratio for  $E_3$ , the number of incidents in Lucia's shifts, he proposes to take account of 'normal' variation of incident rates between nurses and he explains how he would estimate this if relevant data were available (for now, he makes do with a guess). On the other hand, he also has to come up with a probability for the precise number of incidents in Lucia's shifts if she is guilty.

de Vos would like to see the Bayesian approach applied to the case in its totality. The judge will base his verdict on his posterior probability that the suspect is guilty. This would require judges to give their priors in order to motivate their verdicts. It is unclear what the role of the defence would be in this situation: can they reasonably object to the judges' subjective priors?

## 7. An epidemiological approach

Lucy & Aitken (2002, preprint) discuss a different way of modelling cases like this, and we include a discussion of their method here. This method does not rely on conditioning on the number of incidents, but instead presumes availability of epidemiological data.

The basic assumption of Lucy and Aitken is that the probability distribution of the number  $X$  of incidents witnessed by a certain nurse is given by a Poisson distribution, hence

$$P(X = k) = e^{-\mu r} \frac{(\mu r)^k}{k!},$$

where  $r$  is the number of shifts of the nurse and  $\mu > 0$  is a parameter representing the intensity of incidents.

The usual argument for the Poisson distribution in this kind of situation is that it follows from the following assumptions: the numbers of incidents in different time intervals are independent of one another with constant expected rate and several incidents cannot occur at the same time. Since the chance of several incidents in one shift is rather small, these assumptions are very close to those made by Elffers. Indeed, the binomial distribution with small ‘success’ probability  $p$  is very close to a Poisson distribution. (One can therefore make the same objections to this model as to Elffers’: is the incident rate constant? Are incidents at different times independent of one another?)

The hypothesis of chance could now be formulated as saying that every nurse, including the suspect, has the *same* intensity parameter  $\mu$ . (Aart de Vos would allow every nurse to have a *different* intensity; the incident intensities of innocent nurses being drawn from some probability distribution.) The hypothesis  $H_p$  of the prosecutor can have several forms. One possibility is that incidents in Lucia’s shifts also follow a Poisson distribution, but with a different intensity. Then, the prosecutor’s hypothesis might be  $H_p$ :  $\mu_L > \mu$ , where  $\mu_L$  is the parameter corresponding to the suspect and  $\mu$  is the parameter corresponding to all other nurses, neither being specified. How to proceed depends on whether or not  $\mu$  and/or  $\mu_L$  are known or unknown quantities.

### 7.1 Likelihood ratios

One possible approach is to compute likelihood ratios for  $H_p$  against  $H_d$ . Consider a situation with  $I$  nurses, and let  $k_i$  be the number of incidents witnessed by nurse  $i$ ,  $i = 1, \dots, I$ . Denote by  $r_i$  the number of shifts of nurse  $i$ , and let  $E$  be the event that nurse  $i$  witnessed  $k_i$  incidents, for  $i = 1, \dots, I$ . This leads to

$$P(E|H_d) = \prod_{i=1}^I e^{-\mu r_i} \frac{(\mu r_i)^{k_i}}{k_i!},$$

and, assuming that the suspect is nurse  $j$ , to

$$P(E|H_p) = \frac{e^{-\mu_L r_j} (\mu_L r_j)^{k_j}}{k_j!} \prod_{i=1, i \neq j}^I e^{-\mu r_i} \frac{(\mu r_i)^{k_i}}{k_i!}.$$

A simple computation then shows that the likelihood ratio becomes

$$\text{LR} = \frac{P(E|H_p)}{P(E|H_d)} = e^{\mu r_j - \mu_L r_j} \left( \frac{\mu_L r_j}{\mu r_j} \right)^{k_j}. \quad (2)$$

In order to evaluate the outcome of any computation with this likelihood ratio, we may use the following scale for describing the height of a likelihood ratio, see Evett *et al.* (2000).

	Evidence is
LR = 1	equally likely under $H_p$ as under $H_d$
$1 < \text{LR} < 100$	slightly more likely under $H_p$ than under $H_d$
$100 \leq \text{LR} < 1000$	more likely under $H_p$ than under $H_d$
$1000 \leq \text{LR} < 10\,000$	much more likely under $H_p$ than under $H_d$
LR > 10 000	very much more likely under $H_p$ than under $H_d$

As was noted by Meester & Sjerps (2003, 2004), one should be careful when using a table like this if the hypotheses were suggested by the data. In that case, they only become meaningful in combination with prior probabilities for the hypotheses considered. For this reason, we concentrate on the RKZ. However, we still have a problem with data-dependent hypotheses since we need to specify the intensities  $\mu$  and  $\mu_L$  in order to compute the likelihood ratio.

In the following computations, for simplicity we take the data of the two wards at the RKZ together. Above, we have argued that we should allow different incident rates between different wards; in that case, the numbers would come out even better for the suspect.

Clearly, the choice of the parameters is a sensitive and difficult issue. We discuss two possibilities:

- I: One can estimate  $\mu$  using the incidents during shifts of all nurses apart from the suspect; this leads to

$$\mu = \frac{13}{614}.$$

Lucy and Aitken proceed by choosing  $\mu_L$  in such a way that the expected number of incidents witnessed by the suspect is precisely  $k_j$ , i.e.  $\mu_L r_j = k_j$ , hence

$$\mu_L = \frac{6}{61}.$$

These assumptions lead to a likelihood ratio of 90.7, and this is in the range where the evidence is only slightly more likely under  $H_d$ .

- II: Perhaps, one could also estimate  $\mu$  based on all incidents. This leads to

$$\mu = \frac{19}{675}$$

and to a likelihood ratio of about 25 (keeping  $\mu_L$  as above).

If we would apply this method to the JKZ data, prosecution and defence would disagree strongly on how to estimate  $\mu$ . From the point of view of the defence, the first estimate is biased downwards grossly. The precise reason we are analysing these data is because we observed a coincidental concentration of incidents in the shifts of one nurse; we then take the other shifts, with coincidentally few incidents, on which to base our estimate.

### 7.2 Relation to Elffers' approach

As we noted above, the assumptions needed to justify the Poisson model are essentially the same as those *initially* taken by Elffers. Starting from the model of Lucy and Aitken, conditioning on the observed fact that there was never more than one incident in a shift and then conditioning on the total number of incidents, we arrive, under the null hypothesis of chance, at Elffers' hypergeometric distribution. Now, one can also arrive at the hypergeometric distribution from different modelling assumptions; for instance, the chance of an incident in a shift may vary arbitrarily over shifts, but nurses are assigned to shifts completely at random. Thus, the analysis of Lucy and Aitken is more restrictive than that of Elffers. In particular, the Poisson model suffers from all the problems brought up in Section 3.4; also in this model, we must assume that there is no difference between day and night shifts, no variation in case mix over time and so on.

If the normal intensity were known to be equal to  $\mu$ , then using the property of sufficiency, we see that the data of the other nurses are irrelevant and we should simply investigate whether Lucia's number of incidents is large compared to the number expected from a Poisson distribution with expectation  $\mu$  times the number of shifts of Lucia.

If the normal intensity is unknown but we have data from normal working operations (e.g. the other nurses in the same ward), then again sufficiency shows that we should base our inference on the total numbers of incidents of Lucia on the one hand and of the others on the other hand. These numbers will be Poisson distributed with means  $\mu_L r_L$  and  $\mu r$ , respectively, where  $r_L$  and  $r$  are the number of shifts of Lucia and the others, respectively.

This is a classical statistical hypothesis-testing problem. If both means are large, one would use a generalized likelihood ratio procedure based on comparing maximized log likelihoods under the null hypothesis:  $\mu_L = \mu$ , both parameters unknown. However, many statisticians would prefer to use an exact test based on the fact that conditional on the grand total of incidents  $N$ , those of Lucia are binomially distributed with parameters  $N$  and

$$p = \frac{\mu_L r_L}{\mu_L r_L + \mu r}.$$

Under our null hypothesis  $\mu = \mu_L$ ,  $p$  is known, and we have a classical hypothesis-testing problem based on one observation from a binomial distribution. If we have no more data than that reproduced in the paper, then (per ward) the analysis is almost the same as Elffers'.

However, if there truly were more data available, e.g. numbers of incidents and shifts in some adjacent time periods in the same ward, then this has the effect of adding to the total number of shifts and adding to the total number of incidents during the shifts of the others. If we had much of such data and if the incident rate during that time was close to what we observed during Lucia's shifts, then the data would become more and more favourable to Lucia. Hence, *if* we had information on the normal rate of incidents, we would have used it and the conclusion *could* have been very different.

### 7.3 Discussion

The drawbacks of the conditional approach become quite apparent here. In Section 7.2, it became clear that collecting extra data could change the impact of the existing data dramatically, and it would seem the duty of an expert witness to point this out.

However, if reliable data on incident rates cannot be found, this approach leads to essentially the same analysis and conclusions as the corrected Elffers method, see Section 5. Also the likelihood ratio approach, applied to just the RKZ data, leads to much the same conclusion again.

## 8. Relative risk

Lucy & Aitken (2002, preprint) define the term *relative risk* as follows: the relative risk  $R_j$  of a nurse  $j$  is the fraction of her shifts during which an incident took place divided by the fraction of the remaining shifts during which an incident took place. More formally,

$$R_j = \frac{k_j / r_j}{\sum_{i \neq j} k_i / \sum_{i \neq j} r_i}.$$

For example, the relative risk of Lucia for the RKZ for the two wards together is equal to

$$\frac{\frac{6}{61}}{\frac{13}{614}} \approx 4.65.$$

The fact that Lucia had the highest relative risk is clearly not enough to warrant any investigation; some nurse must have the highest relative risk. The more important question is how high a relative risk should be in order to be suspicious.

The distribution of the highest relative risk depends on many variables, like the number of nurses, the way the shifts are spread among the nurses, the number of shifts and of course on the modelling assumptions concerning the occurrence of incidents. In this section, we again concentrate on the model of Lucy and Aitken of Section 7.

The numbers in the definition of the relative risk only depend on the considered time span, comparing the amount of incidents (s)he witnessed to the amount of incidents the other nurses witnessed. It is now useful to do some numerical simulations to obtain some idea about the distribution of the highest relative risk.

### 8.1 Simulating relative risk

We have no data concerning the number of shifts of each other nurse apart from Lucia, and at the RKZ, we do not even know how many other nurses there were. Therefore, we have simulated a situation where all nurses worked the same number of shifts (actually, this should lead to less variability in relative risk since if some nurses work few shifts, their relative risks can more easily be extremely small or large). At the RKZ, we have a total of 675 shifts of which Lucia worked 61 (note the remark after the table of data in Section 2). Therefore, we simulated a situation in which 11 nurses all had 61 shifts. Hence,  $r_i = r$  for all  $i$  and  $I = n/r$ . This leads to

$$R_j = \frac{k_j}{\sum_{i=1}^I k_i - k_j} (I - 1).$$

We are interested in the nurse with the highest relative risk for each group of  $I$  nurses. Since all nurses work the same number of shifts, this is simply the nurse with the most incidents.



We have run 1000 simulations in the case of Lucia for the data of the RKZ, first for both wards together, then for each ward separately. The values for  $\mu$  in the first column are based on the frequency of incidents of all other nurses in the RKZ; the values of  $\mu$  in the second column are based on the overall frequency of incidents, including Lucia (these choices are the same as in Section 7.1).

Whole RKZ	$\mu = \frac{13}{614}$	$\mu = \frac{19}{675}$
Lucia's $p$ -value	0.121	0.042
RKZ-41	$\mu = \frac{4}{333}$	$\mu = \frac{5}{336}$
Lucia's $p$ -value	0.787	0.681
RKZ-42	$\mu = \frac{9}{281}$	$\mu = \frac{14}{339}$
Lucia's $p$ -value	0.383	0.286

## 8.2 Discussion

For  $\mu = \frac{13}{614}$ , Lucia's relative risk of approximately 4.65 lies between the 879th and the 880th of the 1000 highest relative risks. In other words, it is a high relative risk, but not extremely high. For  $\mu = \frac{19}{675}$ , Lucia's relative risk lies between the 958th and the 959th highest relative risks. If we would take  $\mu$  even higher, Lucia's relative risk would have a smaller  $p$ -value.

From this, we may conclude that if data on the number of incidents outside the time span Lucia worked at the RKZ would indicate  $\mu$  to be large, Lucia's relative risk would be extremely high and this could be used as an evidence against her in court. This seems strange since in the likelihood ratio approach of Section 7.1, a larger  $\mu$  implied a *lower* likelihood ratio which is in favour of the defendant (if the Poisson model is correct and  $\mu$  is known, then only the number of incidents in Lucia's shifts is relevant for investigating whether her incidents have the same intensity).

The fact that a large  $\mu$  does not work in favour of the defendant in the relative risk approach is because if  $\mu$  really is very large, then we do not expect much spread in the relative risks of the nurses. If the total number of incidents is coincidentally very small, then the relative risks will be widely spread. So under the hypothesis that all the nurses are the same, whenever the total number of incidents is much smaller than expected, the largest relative risk is likely to be extremely large.

## 9. Conclusion

It is not easy to draw a clear-cut conclusion from all these. Elffers' analysis of the JKZ data perhaps confirms that something surprising has happened there, just as you would be surprised if someone in your street won the state lottery. Indeed, had this computation led to the conclusion that the concentration of incidents in Lucia's shifts was not so surprising, then there would not have been a case against Lucia at all.

So, these numbers did raise interest and suspicion, and there should have been reflection on what to do next. If Elffers used his model correctly, i.e. combining the data from different wards in a statistically justifiable way, moreover, without double use of data (hence, without the need for arbitrary *post hoc* correction), then the resulting numbers would have been very different. In fact, the outcome would not have led to the rejection of the null hypothesis of chance, at significance level of 0.001 (Elffers' own choice), although the  $p$ -value of 0.022 (see Section 5) still leaves one uneasy.

Following the epidemiological approach does not lead to a different conclusion. The likelihood ratios of 90.7 and 25 reported in Section 7 would in itself not lead to conviction, but are again uneasily high. Similar remarks apply to the relative risks in Section 8. de Vos' Bayesian approach does combine all the data. He starts with a rather small prior probability that Lucia is a murderer. He allows natural variation between incident rates between innocent nurses, making Lucia's number of incidents somewhat less surprising (a likelihood ratio of 'only' 7000 for the JKZ data). Together with a small prior probability for Lucia to be a murderer, he arrives at a chance of 10% that she is innocent. However, on the way he has to conjure up one number after another out of thin air.

In contrast to this, the weakness of Elffers' approach can be seen as its strength. Once we have the model, there are no further parameters to be worried about or which could lead to disagreement between prosecution and defence. Convincing rejection of the null hypothesis would mean that the association between incidents and Lucia's shifts is not a coincidence. However, correlation does not imply causation, and alternative explanations of the correlation need to be disqualified before it could be seen as evidence for the case of the prosecution. (The conclusion of the court was that there was a 'connection' between her presence and incidents; the word *connection* is oversuggestive of causality.)

The Poisson model of Lucy and Aitken suffers from the fact that any conclusion by either party can be questioned by the other on the basis of the choice of the parameter  $\mu$ . If one of the parties can raise reasonable doubts about the validity or reasonableness of the parameter choice, then the numbers arising from that model can be questioned as well.

On the other hand, the analysis carried out in Section 7 shows that Elffers' choice to condition on the total number of incidents is tantamount to ignoring what could be a very relevant piece of information.

The more sophisticated a model becomes, the more possibilities for criticizing it one has. This becomes abundantly clear in the Bayesian approach of de Vos in Section 6. de Vos tries to incorporate everything into his mathematical model. To us, this seems impossible, and the result of the computations of de Vos does not mean much.

Can statistics play an important role in a case like this? As we have seen, there is no one correct way to analyse the available data. Every analysis involves subjective choices. The more sophisticated the analysis, the more subjective elements it seems to contain, and hence the more controversial are its conclusions. In fact, perhaps the only uncontroversial number in this paper are the numbers in Section 5. These numbers do not suffer from double use of data or scaling problems nor do they involve any parameter choice. On the other hand, the evidence they give is weak in several respects (weak evidence of correlation, not of causation).

Perhaps, these numbers are—after all—the only possible contribution of statistics to the present case. This statement might be surprising, given the data in the table at the beginning of the paper. But it is one thing to say that a number is relevant and it is quite another thing to work out a reasonable way to use it. Not all numbers can or should be used in a statistical fashion.

On 18 June 2004, the court of appeal in The Hague again found Lucia de B. guilty and sentenced her to life imprisonment plus detention in a psychiatric hospital in case she would ever be pardoned. This time, the judgement made no mention at all of statistical arguments; other evidence which had played a secondary role during the first trial now assumed primary importance. Hence for several reasons, this was a Pyrrhic victory at most (at least for the authors). If the court of appeal had explicitly repudiated the form of statistical argument employed by the public prosecutor and the first court, future cases would have been able to use this jurisprudence.

However, incorporating the statistical argument in the second judgement would have required the court of appeal to take an explicit stand on all the issues raised above. In fact, careful writers on the foundations of statistics have pointed out that evaluating a statistical conclusion involves even more:

In applying a particular technique in a practical problem, it is vital to understand the philosophical and conceptual attitudes from which it derives if we are to be able to interpret (and appreciate the limitations of) any conclusions we draw. (Barnett, 1999, p. 332)

Evidently, the court of appeal was not willing to dig this deep; but the quote as well as the case of Lucia de B. may serve as a reminder to lawyers and judges that the interpretation of statistical arguments is by no means immune to disputation.

Postscript: The case of Lucia de B. was taken to the supreme court, which for the most part upheld the verdict of the court of appeal. However, since this article was written, new evidence concerning this case has surfaced, which also affects the statistical arguments discussed here. As a consequence of this, the case of Lucia de B. will be reviewed by a special committee charged with the investigation of controversial cases. This committee may advise to reopen the case.

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