

## Sketch of replies to N. Comp. reviews

16 March 2020; updated 17 March 2020

### Reviewer 1

(1). First, I would like to direct attention to the paper by Amari, Nakahara, Wu and Sakai in Neural Computation 2003, which the authors also cited in this paper. In this paper, Amari et al showed that "weak higher-order interactions of almost all orders are required for realizing a widespread activity distribution." (Theorem 3). As shown in the case of pairwise model (Eq.3.19 in their paper), if the fixed moments are limited and do not have higher-order, a distribution will be concentrated when we increase the number of neurons.

The suggested ME model by this paper constrains a few moments as opposed to larger number of neurons, which can not result in the wide-spread distributions according to the above theory. In other words, I speculate that the bimodal structure is an artifact of constraining fewer number of moments for a model with such large number of neurons. This could happen even if we use up to all 65th moments. I would like to know how the authors think of Amari's paper in the light of the current manuscript.

We think that the arguments of Amari et al. (2003) do not apply to the inference in our manuscript, for several reasons:

- i. We did perform the calculations with an increasing number of moments as sufficient statistics, eventually using the full sample distribution. As mentioned on p. 9 and shown in § 4, from about 5 moments upwards the final result doesn't change appreciably.

Most important, as we discuss in §§ 6 and 7, our results are the same *without* using any sufficient statistics – that is, *no maximum-entropy* model at all – under a fully Bayesian nonparametric approach. In fact, the fully nonparametric approach leads to slightly wider distributions (we hope to publish these results soon).

- ii. As  $N$  increases, the two peaks we infer do become more pronounced, as suggested by our Fig. 1. So our inference is not really in contradiction with Amari et al.. The results of that paper hold for the  $N \rightarrow \infty$  limit, and no explicit form for the limit-remainder is given there. Limit-reminders such as ' $O(1/N^k)$ ' as given in Amari et al. do not help unless we know their precise form. As an extreme example,  $\frac{10^{10}}{N}$  is  $O(1/N)$ , and in this case the  $1/N$  term cannot really be neglected unless  $N \gg 10^{10}$ . It is therefore unclear whether at  $N = 10\,000$  we should already observe a delta. Our findings [i.](#), above, suggest that we should not.

iii. The results of Amari et al. assume that the probability of the neuronal activity factorizes over time. In our manuscript we assume, as explained in § 6, that our degree of belief is *exchangeable* under time-bin permutations, but this exchangeability *does not imply factorizability* over time, as is clear from de Finetti's theorem. So we are not sure whether Amari et al.'s results apply at all to our inference.

(2) [we can reply by applying to real data.]

(3) I was not satisfied with the section of the Bayes factor. The Bayes factor (Eq.10) was calculated for models with different dimensionality. Then, a larger model should better account for the data. How do you determine whether you include the higher-order or not, in other words how do you determine the significance of the delta? If the models have the same dimension, one may use heuristics, for example given by Kass and Raftery (JASA 1995). If you have nesting models, one may resort to chi-squared test? Just computing the BF without such a verification method, providing the quantity BF adds only marginally to the visual inspection of the distributions.

Let us emphasize, first of all, that the purpose of our paper is to make inferences about the total activity of the larger population, not to decide among different sufficient statistics or correlation orders. Section 4 is meant to show the implications of our method for that kind of discussions. In particular we want to show that *conclusions based on a sample and conclusions based on the larger population can be very different*. Our method can bypass that difficulty, if one wants to use it for such comparisons.

We partly agree with the reviewer's concern, but for different reasons. The simple comparison of the log-evidences is not a problem in itself, as explained below. Our calculation of the log-evidence is missing a factor, which comes from the full Bayesian analysis. This factor, however, should be roughly the same in the calculations from the sample and from the larger population, so our point that the two calculations lead to different conclusions still holds. Under another interpretation our calculation is correct as it is. We explain this below.

In any case, please note that we avoid speaking about 'significance', also as recommended by the American Statistical Association in their recent official statements (ASA 2016; 2019 see especially § 2). When comparing hypotheses  $M_i$  we want their full post-data probabilities  $P(M_i | D)$ , with their continuum of cases. We respect the freedom of other researchers to make dichotomies, if they so prefer. But our personal point of view agrees with the American Statistical Association: any threshold is unnecessary and arbitrary. If a *choice* among the hypotheses has to be made for some purpose (say, hardware algorithm implementation in some automated

device), such choice requires not only the probabilities  $P(M_i | D)$ , but also the utility/loss matrix for the various choices conditional on the various hypotheses (Kadane & Dickey 1980). The choice is then made by maximization of the expected utility, a procedure dictated by some simple rational desiderata (Fishburn 1981; Bernardo & Smith 2000; Jaynes 2003 ch. 13). Some utility matrices can even lead to choosing the hypothesis having *lower* post-data probability; this frequently happens in medical decision problems, see e.g. Sox et al. (2013).

There are many differing, fragmented views on the questions of comparison, complexity, nesting, and ‘penalization’ of models. Our view is close to that expressed in several works, studies, and commentaries<sup>1</sup>, and well-explained in MacKay (1992a). According to this view, which we summarize below, the log-evidence automatically takes care of model complexity. This view hinges on a clear definition of what a ‘model’ is.

If by ‘model’ we mean a family of probability distributions, for example (apart from normalization)

$$\left\{ \exp \left[ -\frac{(x - \mu)^2}{2\sigma^2} \right] dx \mid \mu \in \mathbf{R}, \sigma \in \mathbf{R}_{>0} \right\} ,$$

then model comparison is ill-defined. It may happen that the optimal distribution in family  $\mathcal{F}_1$  assigns more probability to the observed data than the optimal distribution in family  $\mathcal{F}_2$ , and yet  $\mathcal{F}_1$  assigns ‘on average’ lower probabilities to the data than  $\mathcal{F}_2$ . It is not clear how the two families should be compared in this case, or what  $P(D | \mathcal{F}_i)$  is. A hypothesis is ill-defined, or at least useless, if it does not allow us to assign a probability to the data. Such a probability can be obtained if we specify a pre-data probability distribution over the distributions in the family, e.g.  $p(\mu, \sigma | I) d\mu d\sigma$  in the example above. ‘Model’ must be therefore redefined as a family of distributions *and* a pre-data distribution over such family (Dawid 1982; 1993). This redefinition also turns out to be equivalent, under exchangeability, to the specification of a single predictive distribution, that is, a joint probability for any number of data samples. Such a predictive distribution automatically determines a family of parametric distributions and a distribution over such family (Bernardo & Smith 2000 ch. 4; Fortini et al. 2000; Ressel 1985; Lauritzen 1984). This redefinition has several consequences:

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<sup>1</sup> e.g. Good 1950; 1985; Kadane & Dickey 1980; Dawid 1982; 1993; Jones et al. 1986; Chatfield 1995; Copas et al. 1995; Draper 1995; Spiegelhalter et al. 1995; Raftery 1995; Gelman et al. 1995; MacKay 2003; Draper et al. 1996; Hoeting et al. 1999; Clyde et al. 1999; McCullagh 2002; Browne & Draper 2006.

First, two models are different if they have the same family but different distributions over it. In fact they clearly lead to different predictive probabilities on the data space. Two such models are also mutually exclusive,  $P(M_1 \wedge M_2 | I) = 0$ , because we cannot use  $M_1$ 's family distribution *and*  $M_2$ 's family distribution at the same time. It's either-or. This consequence makes sense from a nonparametric perspective, where a parametric model is just a delta-like nonparametric distribution, concentrated on a lower-dimensional manifold (the family above) of the full space of distributions (Draper et al. 1996 p. 761). The notion of nested models becomes unimportant from this perspective. Some authors try to define some 'standard' distribution associated to a family, but we agree with those (e.g. Copas et al. 1979; DeGroot in Lindley et al. 1982) who find such definitions ultimately arbitrary. The pre-data distribution over the family expresses our prior information and is therefore highly dependent on the specific problem. Many such 'standard' distributions lead, moreover, to mathematical singularities.

Second, the 'complexity' of a model cannot be judged from the dimensionality of its family. Models  $M_1$  and  $M_2$  can have the same family, but  $M_1$  can have a family distribution concentrated on a very small region, with respect to that of  $M_2$ . Model  $M_1$  is thus effectively using a smaller parameter range than  $M_2$ . Correspondingly the 'typical set' of data to which  $M_1$  assigns appreciable probability is smaller than the typical set of  $M_2$ : model  $M_1$  is less 'powerful'. The effective dimensionality, complexity, or power of a model is thus best defined by the volume of *data space* that is typical under that model (an 'effective dimensionality' of the family can be calculated from this volume: MacKay 1992a § 4). Most important, it may then happen that a model is more powerful than another even if it is based on a lower-dimensional family (MacKay 1992a § 6; 1992b esp. Fig. 4).

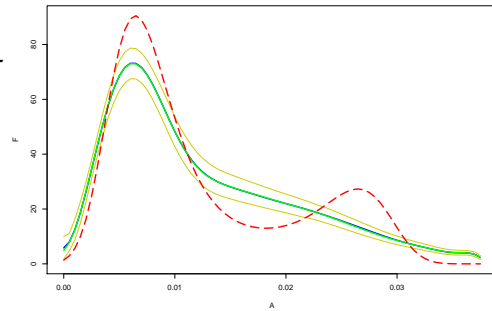
Third, *the evidence*  $P(D | M_i)$  *for a model automatically takes care of its complexity*. This happens because the probability over the data space is normalized. If the more powerful  $M_2$  has a typical-data volume larger than  $M_1$ 's, then it must also assign lower probability to each volume element therein, to ensure normalization. As a result, if the observed data  $D^*$  lie in the typical volumes of both models, then  $p(D^* | M_2) < p(D^* | M_1)$ : *the evidence is automatically penalizing the larger model*. There is a continuous trade-off between how typical the observed data are for each model and each model's power. This is the so-called automatic Ockham razor of Bayes's theorem, extensively explained by MacKay (1992a; also 2003 § 28.1). And this is the reason why we are personally satisfied with simply comparing the evidence for any two models.

In our calculations of the evidence in § 4, however, we are using a zeroth-order Laplace approximation. A first-order approximation (containing the width of the distribution, influenced by the typical-set volume above) would correct for the model’s power (MacKay 1992a § 2.2). We believe that the correction would nevertheless be the same in the calculations based on the larger population, eqs (11), and on the sample, eqs (12). Hence the difference in the two approaches – our main message – should persist. But it would be better to check this.

(4) I enjoyed somewhat philosophical arguments regarding the interpretation of the ME distribution (P8 and Appendix). However, I was not sure how these are relevant to the paper if it is just an interpretation. Can we consider different outcomes arising the different interpretations? If the authors are preparing another manuscript in this direction, these arguments may better be used for that paper? (This is just a weak suggestion.)

Perhaps we chose the wrong term, speaking of ‘interpretation’. What we meant is that the formula we find is valid, as a first approximation, for four different quantities of interest. It is obviously important to specify for which quantities the formula can be used and, among those, for which it provides a better or worse approximation.

On p. 8 we also state that first- and higher-order approximations will be different for each of those four quantities, so their numerical equality is only valid at zeroth-order. Preliminary calculations from the full Bayesian analysis show that the most probable frequency distribution across recorded bins (item i on p. 8) and the belief distribution over the total activity at any recorded bin (item ii on p. 8) are visibly different. See figure on the right: item (i) is the red dashed red curve, item (ii) the solid green line.



Regarding the quantities mentioned on p. 8, it is important to know whether we are calculating the frequency of past results, or the probability for a new result, or the most probable frequency of future results. These quantities can be numerically very different when the ratio  $\frac{\# \text{ samples}}{\text{data-space dimension}}$  is high, and they are to be used in different ways.

These are therefore not philosophical matters. It’s a matter of understanding and clearly stating what we are calculating. There’s also another important reason. We are generally concerned for master’s and PhD students, who often learn concepts and methods through actual research, perusing works like the present one. Young researchers too often end

up learning incorrect or confused ideas, gathered from unclear literature. Sometimes the result, quoting Feynman (1989), is that ‘they don’t learn by understanding; they learn by some other way – by rote, or something. Their knowledge is so fragile!’. We owe them clarity, precision, honesty, and a glimpse of the bigger picture.

## Reviewer 2

2. The method requires that the measurements on  $n$  neurons are ‘representative’ of the full population of  $N$  neurons. The authors show one example, where they divide a dataset into two subsets of neurons with different statistics. They show that the extrapolations from these two subsets are significantly different. But this particular analysis is somewhat ad hoc. Are there any more systematic tests of procedures for understanding how sensitive this analysis is to choosing different subsets of neurons? Or different recoding periods?

\*\*\* equiv to unsystematic sampling for extended recording arrays

3. In particular, correlations tend to be stronger between nearby neurons than far-away neurons. This should be a consistent pattern that shows up in most experimental datasets and which should lead to systematic biases in inferring the properties of populations,  $N$ , which are large enough to result in lower average correlation (see Nonnenmacher et al., PLoS CB 2017). Is there any way to take this dependence into account?

\*\*\* analogous to ‘design’ in survey sampling

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