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MAKING A COLLECTIVE EXPERT DECISION BASED ON THE NEUMANN – PEARSON ALGORITHM

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In the article, we consider the possibility of processing voting results in the case of a team of experts with different efficiency in assessing the situation. The experts were expected to decide whether or not a patient is suffering from a specific disease. The most intelligent combination of the individual expert's votes into a collective council's decision was required. Our algorithm was based on the Neumann – Pearson principle of minimizing the type II error probability at the fixed type I error probability. The team of experts with different qualifications was shown to be able to draw a correct conclusion with high probability.

Keywords: team of experts, assessment efficiency, Neumann and Pearson method

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ПРИНЯТИЕ КОЛЛЕКТИВНОГО ЭКСПЕРТНОГО РЕШЕНИЯ НА ОСНОВЕ АЛГОРИТМА НЕЙМАНА – ПИРСОНА

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В статье рассмотрена возможность обработки результатов голосования в случае коллектива экспертов с различной эффективностью оценки ситуации. Предполагалось, что эксперты должны решить вопрос о наличии или отсутствии у пациента конкретного заболевания. Требовалось наиболее разумно объединить голоса отдельных экспертов в коллективное решение консилиума. В основу построения такого алгоритма был положен метод минимизации вероятности ошибки второго рода при фиксированной вероятности ошибки первого рода (алгоритм Неймана – Пирсона). Показано, что совет, состоящий из экспертов с различной квалификацией, может с большой вероятностью приходить к правильному выводу.

Ключевые слова: коллектив экспертов, эффективность оценки, метод Неймана и Пирсона

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Introduction

Drawing a difficult and non-standard conclusion, as a rule, requires an opinion supplied by a group of experts. In case of selecting several decisions, to arrange the possible options provided by the experts, paired comparison method, ranking, and other methods are used [1, 2]. When choosing a single solution, it is assumed that all experts are equally professional, and an option is considered accepted if it received the maximum number of votes. Many papers [3 – 8] consider the features and drawbacks of such a manner of votes processing.

In the article, we consider the possibility of processing voting results in the case of a team of experts with different efficiency in the situation assessment. It is also implied that the experts need to choose only one of two options. Such an alternative is common, for example, in the course of a medical council when deciding on a certain diagnosis. Using their experience and the data on a certain patient available, the experts attempt to identify which of the two situations they are dealing with: whether a patient is suffering from a specific disease or not.

A necessity of such a choice occurs not only in the medical field. Expert experience is in demand in consulting companies [9], academic and work councils. There is a binary choice, for example, when assigning a candidate to the head position in a company, when there is a need for a decision on whether the candidate has all the essential leader qualities and whether he or she is effective in the future. The experts can also participate in decision making concerning the feasibility of revolutionary enterprise reforming, involvement in a certain investment project, etc.

Application of optimal Neumann – Pearson algorithm to make a collective expert decision

Assume that an expert team consists of G homogenous groups with N_g number of experts in each group. The experts are believed to make decisions independently, including the cases inside one group. Homogenous group can be formed on the basis of their previous work in different medical councils. These groups can be represented by various healthcare facility departments, in each of which voting takes place. The employees of one department may have similar views on the disease symptoms.

Let us denote the a $p_A^{(g)}$ probability that an expert doctor of a g group takes a healthy patient for a healthy one, and a $p_B^{(g)}$ probability that the expert doctor takes an ill patient for a healthy one. Those are conditional probabilities that the expert says “healthy” in situations A and B, respectively. The experts are united in one g group because they have the same probability values $p_A^{(g)}$ and $p_B^{(g)}$. Then the probabilities that the expert is right equal $p_A^{(g)}$ and $1 - p_B^{(g)}$. The probabilities of the right choice may be equal to or satisfy either a $p_A^{(g)} > 1 - p_B^{(g)}$ inequality or a $p_A^{(g)} < 1 - p_B^{(g)}$ inequality. The latter inequality in the medical field, for instance, characterizes a doctor who is apt to overdiagnosis, i.e. misdiagnosing a patient with a disease.

Further, let us denote the number of votes supporting A in the g group using n_g. Unite those values into a voting vector

$$\mathbf{n} = (n_1, n_2, \ldots, n_G).$$

The number of different results of the voting equals

$$M = \prod_{g=1}^{G} (N_g + 1).$$

If we consider that the experts decide independently of each other, then the $\mathbf{n}$ result possibility in the A and B options is expressed as

$$P_A(\mathbf{n}) = \prod_{g=1}^{G} C_{N_g}^{n_g} \left(p_A^{(g)}\right)^{n_g} \left(1 - p_A^{(g)}\right)^{N_g - n_g}, \quad (1)$$

$$P_B(\mathbf{n}) = \prod_{g=1}^{G} C_{N_g}^{n_g} \left(p_B^{(g)}\right)^{n_g} \left(1 - p_B^{(g)}\right)^{N_g - n_g}. \quad (2)$$

Statistics play the key role in building the optimal Neumann – Pearson criterion:

$$K(\mathbf{n}) = \frac{P_B(\mathbf{n})}{P_A(\mathbf{n})}. \quad (3)$$

Let us arrange the possible voting results in $K(\mathbf{n})$ ascending order:

$$K(\mathbf{n}_1) \le K(\mathbf{n}_2) \le \ldots \le K(\mathbf{n}_M). \qquad (4)$$

Introduce a cross section of sequence (4) by means of

$$K_0 = K(\mathbf{n}_{k_0}),$$

where k_0 is the sequence number of the K_0 value in sequence (4).

The choice of the k_0 value is discussed below. A collective decision, according to the Neumann – Pearson criterion, is made depending on which of the following conditions is satisfied for the voting $\mathbf{n} = \mathbf{n}_k$:

$$k < k_0, \qquad (5)$$

$$k = k_0, \qquad (6)$$

$$k > k_0. \qquad (7)$$

In case (5), the A hypothesis is supported, i.e. according to the nomenclature accepted in Mathematical Statistics, the population of such $\mathbf{n}_k$ voting vectors falls to the admissible domain. In case (7), the hypothesis is rejected ($\mathbf{n}_k$ belongs to the critical domain). In borderline case (6), the decision is made statistically: the A hypothesis is rejected with the ε probability, and is supported with the probability of 1 – ε.

For this algorithm, the probability of the type I error equals

$$\alpha = \sum_{k=k_0+1}^{M} P_A(\mathbf{n}_k) + P_A(\mathbf{n}_{k_0})\varepsilon. \qquad (8)$$

The probability of the type II error is given by an expression

$$\beta = \sum_{k=1}^{k_0-1} P_B(\mathbf{n}_k) + P_B(\mathbf{n}_{k_0})(1-\varepsilon). \qquad (9)$$

In the Neumann – Pearson algorithm, the probability of the type I error can be set arbitrarily, while the algorithm provides the minimal probability of the type II error with the set value of the type I error probability.

Then, the k_0 and ε parameters are chosen with such a condition in mind according to which the type I error probability α takes the set value. From relation (8), we obtain:

$$k_0 = \max k, \quad \sum_{l=k}^{M} P_A(\mathbf{n}_l) \ge \alpha;$$
$$\varepsilon = 1 - \frac{\sum_{l=k_0}^{M} P_A(\mathbf{n}_l) - \alpha}{P_A(\mathbf{n}_{k_0})}. \qquad (10)$$

Let us explain the meaning behind the Neumann – Pearson criterion optimality. Consider a certain arbitrary criterion of making a collective decision defined by a function

$$\varphi_1(\mathbf{n}_k) \quad (0 \le \varphi_1(\mathbf{n}_k) \le 1). \qquad (11)$$

This function equals the probability of the A hypothesis being rejected, and respectively, with the probability of 1 – $\varphi_1(\mathbf{n}_k)$ being supported in case of the $\mathbf{n}_k$ voting result. The corresponding function for the optimal criterion according to Eqs. (5) – (7) has the form

$$\varphi(\mathbf{n}_k) = \begin{cases} 0, & k < k_0; \\ \varepsilon, & k = k_0; \\ 1, & k > k_0. \end{cases}$$

Assume that α_1 and β_1 are the probabilities of the type I and type II errors for criterion (11). The Neumann – Pearson criterion is optimal in a sense that at any choice of function (11) the condition

$$\alpha_1 \le \alpha \Rightarrow \beta_1 \ge \beta.$$

is satisfied.

This excludes a case when some criterion has the type II error probability lower than the optimal criterion has at the same or lower levels of the type I error probability.

The optimality can be formulated more graphically, if we introduce a notion of comparable criteria with respect to accuracy. Let us assume that two criteria are comparable if the probabilities of type I and II errors of one of them deviate from the respective probabilities of the other criterion in one way. We can naturally call the criterion with lower error probabilities more accurate. In these terms, the optimal criterion is more accurate than any comparable criterion or both criteria have the same accuracy.

Eqs. (10) and (9) allow us to construct the function

$$\beta=\beta(\alpha).$$

The choice of the type I error probability α is arbitrary, and using the Neumann – Pearson algorithm for each of its value we obtain the minimum possible probability of the type II error.

If we know the a priori probability of the *A* option (let us denote it as P_A), then we can set the following task: to select α in such a way, as to obtain the minimum possibility of the total error in making the decision

$$\gamma(\alpha)=P_A\alpha+(1-P_A)\beta(\alpha). \quad (12)$$

This value of α_{opt} is determined by the formula

$$\alpha_{opt}=\arg\min_{\alpha}\gamma(\alpha). \quad (13)$$

Example of calculation with the optimal algorithm

Let us present an actual example of calculations based on the optimal criterion. Consider a medical council consisting of two groups. The council parameters are given in Table 1. The results of applying the optimal criterion to the process collective decision making of this council are displayed in Table 2.

The second Table shows various voting results ranked by the value of (3). The rightmost column presents the $K(\mathbf{n})$ values. The second and the third columns (on the left) give the number of votes supporting the *A* option in each of the two groups: values n_1 and n_2, respectively.

The fourth column on the left shows the probability of the respective voting result in an assumption that the experts are presented with the *A* option. The fifth column on the left includes a cumulative probability: the probability of this result or any other (it is located below). The second and the third columns on the right contain similar information, but the experts are considering the *B* option. Moreover, the cumulative probability is calculated for the voting results located above the one under consideration. The cumulative probabilities serve for the purpose of calculating the statistical errors (see the text below).

Assume that the sequence of the voting results given in Table 2 is arbitrarily divided into the upper and the lower parts. The Table demonstrates the division at the state with the sequence number $k = k_0 = 4$. According to the optimal criteria, the states located below the border, i.e. the numbers of the line put in bold red type, belong to the critical domain, while the states above the border fall into the admissible domain. If a voting result falls into the critical domain, then the experts support the *B* option. If a voting result is located in the admissible domain, then the decision is made in favor of the *A* option. If the voting ends in the borderline case, then the *B* option is supported with the ε probability and the *A* option is supported with the 1 – ε probability.

Table 1

Medical council parameters

Group number	Number, people	p_A	p_B
1	3	0.90	0.20
2	2	0.95	0.10

The possibilities that an expert doctor takes a healthy patient for an ill patient (p_A) and an ill person for a healthy one (p_B) are presented.

Table 2

Council voting results and their probability parameters

Seq. number k	Vector of voting for option A $\mathbf{n} = (n_1, n_2)$		Option A		Option B		$K(\mathbf{n})$
1	3	2	0.658	1.00	0.00008	0.00008	0.000122
2	2	2	0.219	0.342	0.00096	0.00104	0.00438
3	3	1	0.0693	0.123	0.00144	0.00248	0.0208
4	**1**	**2**	**0.0244**	**0.0535**	**0.00384**	**0.00632**	**0.158**
5	2	1	0.0231	0.0291	0.0173	0.0236	0.749
6	3	0	0.00182	0.00606	0.00648	0.0301	3.56
7	0	2	0.000902	0.00424	0.00512	0.0352	5.67
8	1	1	0.00257	0.00334	0.06912	0.104	26.9
9	2	0	0.000608	0.000773	0.0778	0.182	128
10	0	1	0.000095	0.000165	0.0922	0.274	970
11	1	0	0.0000675	0.00007	0.311	0.585	4610
12	0	0	0.0000025	0.0000025	0.0415	1.00	166000

Thus, the border is statistically blurred: with the probability of ε it falls into the critical domain, while it belongs to the admissible one with the 1 – ε probability. It is clear from the above that after the choice of the values

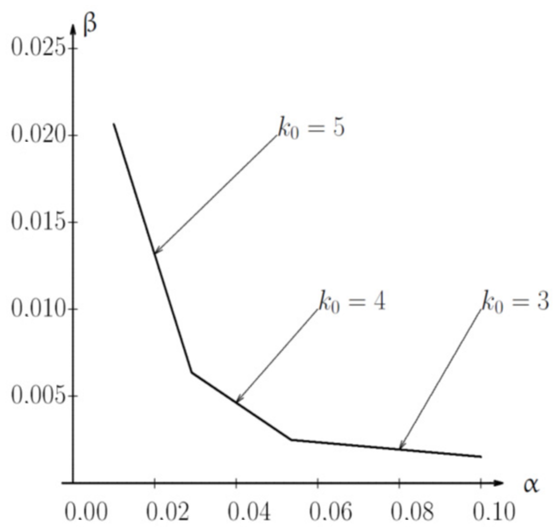
$$k_0 \text{ and } \varepsilon\left(1 \le k_0 \le 12,\, 0 < \varepsilon \le 1\right)$$

the type I and II error probabilities are equal to:

$$\alpha = \sum\nolimits^{(A)}_{k_0+1} + \varepsilon \cdot P^{(A)}_{k_0},$$
$$\beta = \sum\nolimits^{(B)}_{k_0-1} + \left(1-\varepsilon\right) \cdot P^{(B)}_{k_0}, \qquad (14)$$

which is in agreement with Eqs. (8) and (9).

The Figure shows a fragment of the β(α) function graph for the α values of interest and model parameters presented in Table 1. Note that the dependence of β on α is piecewise linear which results from Eq. (14). Indeed, with a continuous increase in α, at first the ε value grows at the constant value of k_0. Then, when ε reaches it maximum value of ε = 1, the k_0 value drops by one, the cumulative probability $\sum\nolimits^{(A)}_{k_0+1}$ increases by $P^{(A)}_{k_0}$, while the ε value becomes zero. With the further growth of α the ε value increases again, and the whole process repeats itself. We can see from Eq. (14) that the β value has a linear dependence on ε. Therefore, at the regions where α changes, while k_0 is fixed, β a linear dependence on α. The



Example of a dependence of the type II error probability on the type I error probability (model parameters are given in Table 1)

Figure shows three of such linear dependence regions. At the peaks of the broken line the value $\varepsilon = 1$, which means the stochastic element of the optimal criterion disappears at such values of α.

It follows from the piecewise linear nature of the $\beta(\alpha)$ function that the probability of the total error $\gamma(\alpha)$ has the same property (see Eq. (12)). But then the task of minimizing the $\gamma(\alpha)$ function (see Eq. (13)) as its solution has a value of α corresponding to one of the peaks. At those peaks, $\varepsilon = 1$ and the criterion is stochastic. Thus, in the frame of a rather generalized task setting, the Neumann – Pearson criterion does not contain a randomized element. If we take into account the fact that in case of continuous distribution the randomization is missing entirely [11], we can say that the optimal criterion in practice is often deterministic.

The method presented in this paper allows rational combination of votes of individual expert doctors into a collective conclusion of the council. This algorithm of collective decision making is optimal in the sense described above. The previous paragraph shows that even a council consisting of the experts of different qualification can make the right decision with high probability. This situation is akin to lowering the computational error by means of their independence and massive character. Similarly, in case of collective decision making, it is critical that the experts providing their conclusions are independent of each other. This condition may be subject to a breach in real life due to various reasons. For example, in the course of collective discussion of a diagnosis, each specialist might be inclined to unify the opinions of the council members. Some experts might exert unintentional pressure (for instance, due to their authority) on other specialists. All of these factors may contribute to both an increase or a decrease of the probability of the right collective decision.

Some misconception widely spread among the specialists of these group might be another possible cause for a deviation from independent reasoning of an expert. This may lead to emergence of a statistical dependence (correlation) between opinions of some experts, although in this case they do not interact with each other directly.

Let us note that the independence of the expert decision making is not an essential precondition to the use of the optimal criterion. If there is a correlation, Eqs. (1) and (2) become invalid. However, if there are sufficient data on the dependence, we can write the corresponding formulae even in the presence of the correlation instead.

Conclusion

We studied a possibility of processing voting results in case of a team consisting of experts with different qualification. As an example, we considered a case in medical sphere when a medical council was expected to decide whether or not a patient is suffering from a specific disease. The most intelligent combination of the individual expert's votes into a collective council's decision was required. Our algorithm was based on the Neumann – Pearson principle of minimizing the type II error probability at the fixed type I error probability. We tested the developed algorithm by using a simple example: two councils that included 2 and 3 experts. The team of experts with different qualifications was numerically shown to be able to draw a correct conclusion with high probability. The considered methods are recommended for application both in medical personnel training [15, 16], as well as in similar situations demanding an expert group conclusion.

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