Games and Economic Behavior 158 (2026) 122–131

Contents lists available at ScienceDirect

Games and Economic Behavior

journal homepage: www.elsevier.com/locate/geb

Failing to correctly aggregate signals ★

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ARTICLE INFO

JEL classification:
C72
D70
D80

Keywords:
Signal aggregation
Opinion formation
Voting game

ABSTRACT

Individuals fail to recognize that two weak positive signals of a rare event together constitute strong evidence for the event. We demonstrate the dramatic effect of replacing Bayesian aggregation of signals with commonly used aggregation procedures in a simple model of opinion formation and a model of strategic voting.

1. Introduction

We ask the reader to consider the following question:

The proportion of newborns with a specific genetic trait is 1%. Two conditionally independent screening tests, A and B, are used to identify this trait in all newborns. However, the tests are not precise. Specifically, it has been found that:
70% of the newborns who are found to be positive according to test A have the trait.
20% of the newborns who are found to be positive according to test B have the trait.
Suppose that a newborn is found to be positive according to both tests. What is your estimate of the probability that this newborn has the trait?

Notice that the properties of the two tests are described differently than they would be in standard economic theory. Usually, the tests would be described by the chances of a positive or negative result conditional on whether or not the newborn has the trait. In contrast, the question reports the likelihood of the trait given a positive result in either test. This type of description is widely used in real life. In medicine, for example, the results of a test are often assessed in terms of their *positive predictive value* (PPV) which is defined by the NIH as: "The likelihood that an individual with a positive test result truly has the particular gene and/or disease in question."[1] Similarly, the effectiveness of an alarm system is often measured by the *false alarm ratio* (FAR), which is "the number of

★ We are grateful to Ayala Arad whose comments triggered this project, to Noga Alon and Michael Richter who suggested a proof for one of our results and to Aron Tobias for his insightful and generous comments at various stages of the paper. We also thank Sergiu Hart for his suggestions. Our special thanks go to Theodore Turocy, Anwar Ruff and Shayne Trotman for their generous assistance in organizing the surveys.

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[1] https://www.cancer.gov/publications/dictionaries/genetics-dictionary/def/positive-predictive-value

https://doi.org/10.1016/j.geb.2026.02.003
Received 12 August 2024
Available online 11 March 2026
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false alarms per the total number of warnings or alarms in a given study or situation".[2] And just as importantly, this is the way we relate to a multitude of signals in daily life, such as the chances of snow when predicted by a weather forecaster, or the likelihood that someone is at the door when the dog barks.

In the case of only one test, the above question is trivial: neither the prior nor the distribution of the signal given the states of the world is of any use. In the case of two tests, on the other hand, Bayesian updating is more complex and does depend on the prior.

Suppose that $s \in (0,1)$ is the frequency of the trait and that a proportion $\phi_k \in [s,1)$ of the individuals who tested positive according to test k ($k = 1,2$) indeed have the trait. Denote by p_k and n_k the probabilities of a positive result in test k for a newborn with the trait and a newborn without the trait, respectively. By standard Bayesian updating:

$$\frac{\phi_k}{1-\phi_k} = \frac{sp_k}{(1-s)n_k}.$$

Denote by π the probability that a newborn who is found positive on both tests has the trait. Then:

$$\frac{\pi}{1-\pi} = \frac{sp_1p_2}{(1-s)n_1n_2} = \left(\frac{1-s}{s}\right)\frac{\phi_1\phi_2}{(1-\phi_1)(1-\phi_2)}.$$

Notice that: (i) π depends on s, (ii) if $\phi_1 = s$ then test 1 can be ignored and $\pi = \phi_2$, and (iii) given ϕ_1 and ϕ_2, π is close to 1 when s is very small. In our scenario, the probability that the newborn has the trait is $\pi = 0.983$!

Thus, Bayesian analysis leads to an unintuitive conclusion: when the trait is rare, two positive results indicate a high probability of the trait even if neither test is especially accurate. This can be significant in a variety of contexts: In medicine, the positive results of two conditionally independent tests for a rare disease might be concerning even though each result is not particularly alarming on its own. In legal proceedings, two conditionally independent clues about the guilt of a suspect, each unpersuasive on its own, may be strong evidence when considered jointly.[3]

We conjecture that most individuals would fail to compute the correct probability and would themselves be surprised by the correct answer, as were many of our colleagues when presented with the above question. The sharp contrast between Bayesian updating and individuals' intuitions, some of whom work professionally with probabilities, is the *puzzle* that motivates this paper.

The observation that in a variety of circumstances individuals fail to update beliefs via Bayes' rule is certainly not new. Introspection and a large psychological literature cast doubt on the hypothesis that Bayesian updating procedures resemble those used in real life, even when the information needed to form Bayesian posteriors is available and easily interpreted. In particular, much attention has been devoted to the "base-rate fallacy", identified in Kahneman and Tversky (1973) and elucidated in Bar-Hillel (1980). For a survey of the literature on errors in probabilistic reasoning, see Benjamin (2019) and for a survey of decision-making heuristics, see Gigerenzer and Gaissmaier (2011). In our context, the most relevant analysis is to be found in Budescu and Yu (2006) who present evidence that individuals tend to aggregate information from multiple sources by averaging.

Our own evidence, based on surveys reported in Section 2, confirms this. It also highlights some other intuitive non-Bayesian methods of signal aggregation. In particular, we find that to answer the above question individuals tend to use rules which lead to the answers 14%, 20%, 45%, 70% or 76%. These correspond to five simple formulae:

M: $\phi_1\phi_2$
Min: $min\{\phi_1,\phi_2\}$
Avg: $(\phi_1+\phi_2)/2$
Max: $max\{\phi_1,\phi_2\}$
M^c: $1-(1-\phi_1)(1-\phi_2)$

Of these rules, only M^c is qualitatively consistent with the conclusion that both tests contribute positively to the posterior probability and thus the answer should exceed the larger of ϕ_1 and ϕ_2. Yet, even M^c fails to yield the conclusion that when the prior is small two moderately positive signals indicate a high probability of an event.

Since the above procedures for non-Bayesian belief aggregation are evident and intuitive, and since Bayesian updating is unintuitive and rarely used, it is of interest to examine the implications of replacing Bayesian updating with some of the aforementioned rules. We investigate two models in which the conclusions are strikingly different from the standard analysis. We wish to emphasize that our objective is a simple theoretical exercise: we are not claiming that these models are realistic or more suited to various applications. Nor do we intend to contribute to the large literature on the two models. Our purpose is limited to highlighting the peculiarity of the commonly made assumption that individuals follow anything close to Bayesian reasoning.

The first model is a simple description of opinion formation in a society. There are two possible states of nature. An "opinion" is a belief about the state of nature. A "newcomer" to the society receives a private signal about the state as well as the opinion of one sampled individual from the population. We assume that the newcomer forms his belief by averaging the probabilities of the state estimated using these two signals. A distribution of opinions is stable if a newcomer's final belief has the same distribution as the beliefs of the existing members of the society. We characterize the unique stable distribution and show that it cannot fully reveal the state of nature, in contrast to the case in which all agents use Bayesian reasoning.

The second model is a special case of the voting game in Duggan and Martinelli (2001). A group of jurors is to decide whether to convict or acquit a defendant. Conviction requires a unanimous decision. Each juror receives a private assessment of the probability that the defendant is guilty. As is standard in this type of analysis, a juror aggregates his private belief with a fictitious equilibrium

[2] https://www.statisticshowto.com/false-alarm-ratio-definition/

[3] For a discussion of aggregation in law, see Porat and Posner (2012).

signal, that is, the event that all other jurors voted to convict (and thus he is pivotal). In Duggan and Martinelli (2001) agents aggregate signals in a Bayesian way and in the specific case that we consider, if the number of agents is large enough, then the correct decision is made with probability close to 1. We show that:
(1) If all the jurors use the Avg procedure and the number of jurors is large, then almost all defendants are acquitted.
(2) If all the jurors use the Max procedure and the number of jurors is large, then all guilty defendants are convicted, as well as some proportion of the innocent ones. Remarkably, the level of welfare converges to that achieved when the jurors never convict.
(3) While a "large" Bayesian jury can approximate the first-best, other types of "large" non-Bayesian juries achieve the same level of welfare in the limit as a jury that never convicts, even though the jurors use different equilibrium strategies.

2. Survey evidence

The intuition that people fail to recognize that two moderate and conditionally independent signals of a rare event aggregate to significant evidence of the event was confirmed in several discussions with colleagues familiar with probability theory, many of whom were surprised by this feature of Bayesian updating. We conducted a survey which showed that only a small minority of people reach the correct conclusion and that the majority use one of the formulae mentioned in Section 1.

The main survey was carried out at the Center for Experimental Social Science at New York University (NYU) and the Centre for Behavioural and Experimental Social Science at the University of East Anglia (UEA).[4] Students registered with the labs were invited to participate[5] and each participant was assigned randomly to answer one of five questions.

Before proceeding, it is worth clarifying a methodological point related to our interpretation of the experimental data. Our objective is not to find the real-life distribution of updating procedures in inference problems such as Q1. Given the vagueness of the relevant population, conclusions about real-life distributions of behavior are pointless. The results in this section are presented only to demonstrate that a large majority of subjects update beliefs using a few simple and identifiable procedures that are incompatible with the Bayesian approach.

The surveys did not use any monetary incentives. The necessity of such incentives is a controversial issue within the experimental literature. While this is not the place to expand on this controversy, it is clear what side we take. Monetary incentives are likely to affect the results. However, since our intention is only to demonstrate the popular use of non-Bayesian methods and since the exact distribution in the population is not of interest to us, we can set aside the issue of whether monetary incentives are beneficial or harmful.

The questions were similar to the one presented in the introduction except for two main differences. First, we provided a non-technical description of conditional independence. Second, in four of the five questions, the ex-ante frequency of the trait of was given as "a very small proportion" rather than 1%. Here is Q1 as it appeared in the survey:

> **Q1:** A very small proportion of the newborns in a certain country have a specific genetic trait.
> Two screening tests, A and B, have been introduced for all newborns in order to identify this trait. However, the tests are not precise. A study has found that:
> 70% of the newborns who are found to be positive according to test A have the genetic trait (and conversely 30% do not).
> 20% of the newborns who are found to be positive according to test B have the genetic trait (and conversely 80% do not).
> The study has also found that when a newborn has the genetic trait, a positive result in one test does not affect the likelihood of a positive result in the other. Likewise, when a newborn does not have the genetic trait, a positive result in one test does not affect the likelihood of a positive result in the other.
> Suppose that a newborn is found to be positive according to both tests. What is your estimate of the likelihood (in %) that this newborn has the genetic trait?

In Q2, we changed the probabilities to 80% and 60% instead of 70% and 20%. In Q3, we changed the underlying story by replacing newborns with **undergraduates** who are either continuing on to graduate school or not. A positive result on a test is replaced by a student having taken a certain course. The proportion of students who continue on to graduate school is 70% for those who took course A and 20% for those who took course B. The results for Q1, Q2 and Q3 are presented in Table 1.

Note that under the assumption that "a very small proportion" is interpreted as being at most 5%, a correct answer in Q1 and Q3 is at least 91% and in Q2 it is at least 98%. The proportions of those answers appear in the first column.

As shown in the table, a majority (about 60%) of the participants used one of the four formulae: M, Avg, Max or M^c. Around 20% chose an answer strictly above the larger of ϕ_1 and ϕ_2, which is qualitatively correct. There do not appear to be any significant differences in the results between the three questions. The median response time (MRT) was also quite similar in all three, ranging from 98 to 118 seconds.

Q4 was used to check the consistency of the approaches used by the participants. It asked them to simultaneously estimate the likelihood of the trait given two different pairs of test results: Alice tests positive on the two tests with accuracy of 70% and 20%,

[4] We are indebted to the Centre for Behavioural and Experimental Social Science at The University of East Anglia, and especially to Theodore Turocy, and to the Center for Experimental Social Science at New York University, and especially to Anwar Ruff and Shayne Trotman, who were so generous with their time.

[5] At UEA, one out of ten students received 20 pounds for participating and at NYU each student received $10. Students were not incentivized in any other way. We do not report the results for each center separately since the differences were negligible.

Table 1
Results for Q1, Q2 and Q3.

	"correct"	*n (MRT)*	M	Avg	Max	$> Max\ (M^c)$	*Other*
Q1genetic, 70-20	3%	93 (118s)	14%	20%	14%	20% (4%)	32%
Q2genetic, 80-60	1%	91 (107s)	21%	27%	15%	18% (11%)	19%
Q3students, 70-20	1%	97 (98s)	7%	27%	20%	21% (6%)	25%

Table 2
Results for Q5.

	"correct"	*n (MRT)*	M	20%	Avg	Max	$> Max\ (M^c)$	*Other*
Q5	17%	94 (121s)	10%	13%	9%	17%	16% (3%)	36%

respectively and Bob tests positive on the two tests with accuracy of 50% and 40%, respectively. We observe a considerable degree of consistency. Of the 92 participants, about 60% were consistent in their use of one of the four formulae: M (15%), Avg (30%), Max (13%) and M^c (2%). Furthermore, 8% of the participants consistently gave answers above Max which differed from the answer according to M^c. There were no correct answers.

Q5 is identical to Q1 except that the base rate is 20% (rather than "a very small proportion"). As noted earlier, when the base rate is equal to ϕ_1, the correct answer is ϕ_2. Nonetheless, all four formulae were used in this question. About 17% gave the right answer but it is unclear whether it was for the right reason or was based on the Max formula. About 13% gave the base-rate probability (20%) as their answer. One-sixth of the participants chose an answer strictly above both ϕ_1 and ϕ_2, although in this question any answer other than 70% is qualitatively incorrect (Table 2).

3. Aggregation of opinions

In this section, we consider a simple model of aggregation of opinions. There is a large literature on this subject which we ignore. It is perhaps worth emphasising again that our choice of models is purely instrumental. We do not view the exercise that follows as a contribution to this literature beyond demonstrating the importance of the unrealistic assumption that all agents use Bayesian updating.

There are two equally likely states of nature: a and b. There is a population of agents, each with his own belief about the state which we define always as the probability of state a. Denote by F_a the distribution of beliefs for state a in the population when the true state is a and by F_b the distribution of beliefs for state a (!) in the population when the true state is b.

A "new" agent receives a "personal" private signal that declares the state of nature. The signal is incorrect with probability $0 < \epsilon < \frac{1}{2}$. The agent is aware that his signal may be incorrect and thus his belief (the probability of state a) conditional on state $s = a, b$, and given his personal signal is a random variable which we denote by Y_s. In particular, Y_a has the value $1 - \epsilon$ with probability $1 - \epsilon$ and ϵ with probability ϵ and Y_b has the value $1 - \epsilon$ with probability ϵ and ϵ with probability $1 - \epsilon$.

A new agent also samples one belief from the population of agents. We will refer to the outcome of this sampling process as the "sample signal". For a state $s = a, b$, denote by X_s a random variable, conditionally independent of Y_s, which is distributed according to F_s. In contrast to the personal signal, the distribution of the sample signal is endogenous, as will be shown below.

Given a state, the aggregation of the personal signal and the sample signal by the new agent, whatever the method used, yields a belief that is itself a random variable. We will look for distributions of beliefs in the population F_s, $s = a, b$, such that the new agent's beliefs, given the personal signal and the sample signal, are also distributed according to F_s. We refer to such distributions as *stable* and to (F_a, F_b) as a *stable pair*.

It is easily verified that if all agents are Bayesian, then a pair of distributions that reveals the true state is stable. That is, there is a stable pair of distributions such that according to F_a the entire population believes that the probability of state is a is equal to 1 and according to F_b the entire population believes that the probability of state a is equal to 0. We are unable to establish whether this is the unique stable pair.

The above conclusion does not hold if agents update their beliefs using the *Avg* procedure. One notable feature of the *Avg* procedure – and also of the *Max* procedure – is that the outcome of the aggregation in a state s is a random variable which depends on F_s alone but not on the distribution given the other state, as in Bayesian updating. Thus, we can study the stability of F_a and F_b independently.

Now assume that the agents update their beliefs by averaging the two estimates obtained from the personal signal and the sample signal. Stability is now equivalent to finding for each state s a random variable X_s, independent of Y_s, such that $(X_s + Y_s)/2$ is distributed as X_s. A solution was suggested to us by the mathematician Noga Alon and modified by Michael Richter:

Lemma 1. *Let Y be a bounded random variable. There is then an independent random variable X distributed as $\lambda Y + (1 - \lambda)X$.*

Proof. Let $(Y^t)_{t=0,1,2,\ldots}$ be a sequence of independent random variables distributed as Y. Let $X = \sum_{t=0} \lambda(1-\lambda)^t Y^t$. Then,

$$\lambda Y + (1 - \lambda)X = \lambda Y + \sum_{t=0} \lambda(1 - \lambda)^{t+1} Y^t \sim X.$$

□

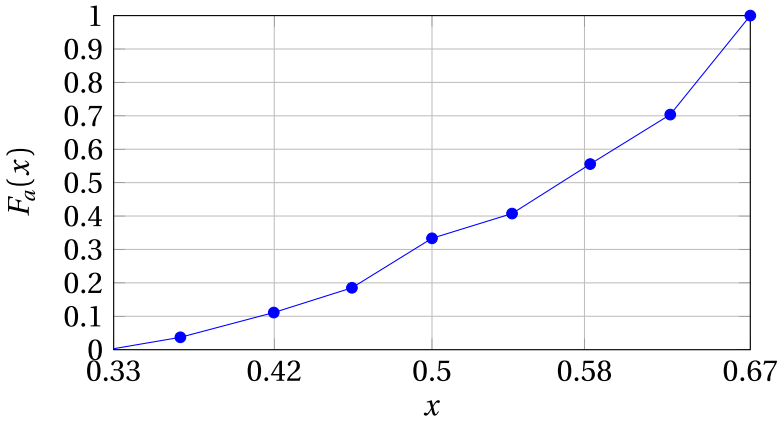

Fig. 1. Plot of $F_a(x)$.

Claim 1. *If all agents use the Avg procedure then the stable pair of distributions is unique. In addition, each distribution is atomless and strictly increasing.*

Proof. For existence, consider the random variable Y_s defined earlier. By the above lemma, there is an independent random variable X_s such that $(X_s + Y_s)/2$ is distributed as X_s.

For uniqueness, it suffices to show that the values of a stable distribution F_a are uniquely determined on a dense set (by symmetry it will follow that F_b is also unique).

First note that for a stable F_a, the following equation must be satisfied for any y:

$$F_a(y) = \epsilon F_a(2y - \epsilon) + (1 - \epsilon)F_a(2y - 1 + \epsilon).$$

We now show that $F_a(\epsilon) = 0$ and $F_a(1 - \epsilon) = 1$. Let y be the smallest x such that $F_a(x) = F_a(\epsilon)$. Since $2y - \epsilon \le \epsilon$, then $F_a(2y - \epsilon) \le F_a(y)$. Furthermore, since $2y - 1 + \epsilon < y$ if $F_a(\epsilon) > 0$ then $F_a(2y - 1 + \epsilon) < F_a(\epsilon)$ and thus the above equation cannot hold. Therefore, $F_a(\epsilon) = 0$.

Suppose that $F_a(1 - \epsilon) < 1$. Define $\hat{y} = sup\{x : F_a(x) = F_a(1 - \epsilon)\}$. If $\hat{y} = 1 - \epsilon$ then $F_a(2(1 - \epsilon) - \epsilon) > F_a(1 - \epsilon)$ (since $\epsilon < 1/2$) contradicting the above equation for $y = 1 - \epsilon$. Otherwise $\hat{y} > 1 - \epsilon$. Then choose $y < \hat{y}$ arbitrarily close to $\hat{y}$. Since $2y - \epsilon > \hat{y}$ and $2y - 1 + \epsilon > \hat{y}$, for y sufficiently close to $\hat{y}$, the above equality cannot hold for such y.

Define the set $D_k = \{d_{n,k}\}_{n=0,1,\ldots,2^k}$ where $d_{n,k} = \epsilon + n\frac{1-2\epsilon}{2^k}$. The set D_0 includes $d_{0,0} = \epsilon$ and $d_{1,0} = 1 - \epsilon$. The set D_{k+1} includes D_k and all the half-points between neighboring points in D_k. Let $D = \cup_{k=1,2,\ldots} D_k$. Obviously, D is dense in $[\epsilon, 1 - \epsilon]$.

The average belief is below a point $x < 1/2$ if and only if the belief based on the personal signal is ϵ and based on the sample signal is at most $2x - \epsilon$. Thus, $F_a(x) = \epsilon F_a(2x - \epsilon)$. It follows that the value of F_a at $d_{n,k} < \frac{1}{2}$ is determined uniquely by $\epsilon F_a(2d_{n,k} - \epsilon)$ where, by definition, $2d_{n,k} - \epsilon = d_{n,k-1}$. Similarly, the average belief is below a point $x \ge 1/2$ if and only if (i) the belief based on the personal signal is ϵ or (ii) the belief based on the personal signal is $1 - \epsilon$ and based on the sample signal is at most $2x - 1 + \epsilon$. It follows that $F_a(x) = \epsilon + (1 - \epsilon)F_a(2x - 1 + \epsilon)$. Therefore, the value of F_a at $d_{n,k} \ge \frac{1}{2}$ is determined uniquely by $F_a(2d_{n,k} - 1 + \epsilon)$ where, by definition, $2d_{n,k} - 1 + \epsilon = d_{n-2^{k-1},k-1}$. Thus, the values of F_a on D_k are determined uniquely by the values on D_{k-1}. It follows that F_a is uniquely determined on the dense set D and the claim is proved.

The second part of the claim follows easily from the above construction. □

To illustrate the proof, consider $\epsilon = 1/3$:

points	values of F
D_0	$F(1/3) = 0,\ \ F(2/3) = 1$
$D_1 - D_0$	$F(1/2) = 1/3$
$D_2 - D_1$	$F(\frac{5}{12}) = \frac{1}{9},\ F(\frac{7}{12}) = \frac{5}{9}$
$D_3 - D_2$	$F(\frac{9}{24}) = \frac{1}{27},\ F(\frac{11}{24}) = \frac{5}{27},\ F(\frac{13}{24}) = \frac{11}{27},\ F(\frac{15}{24}) = \frac{19}{27}$

Note that the function F_a is neither convex nor concave. Aron Tobias drew our attention to the fact that Billingsley (1995) (page 409) uses this function as an example of a distribution function, increasing in its support, that has a derivative equal to zero almost everywhere (Fig. 1).

In the Max procedure, it is of course essential to specify whether the operation is performed on the probability of state a or of state b. Here, we choose state a. In particular, we assume that when the new agent's belief based on the private signal for state a is α and the sampled belief for state a is β, his inference is that the probability of state a is $max\{\alpha, \beta\}$. This specification does affect which distributions are stable. Note that this observation also applies to the Min, M^c and M procedures.

Claim 2. *If all agents use the Max procedure then in each state, a distribution is stable if and only if it assigns probability equal to zero to any belief strictly below $1 - \epsilon$.*

Proof. Obviously, such a distribution is stable as the outcome of the sample is always the larger of the sample signal and the private signal and thus the beliefs of a new agent are distributed according to the distribution in the population.

Let G_s be a stable distribution at state s and let m_s be the probability that beliefs are strictly below $1-\epsilon$ according to G_s. At state s, a new agent will have a belief below $1-\epsilon$ only if (i) according to his personal signal the probability of state a is ϵ, which happens with probability δ_s (which is either ϵ or $1-\epsilon$ and thus strictly below 1), and (ii) his sample signal is below $(1-\epsilon)$ (which has probability m_s in state s). However, $m_s\delta_s \neq m_s$ unless $m_s = 0$. Therefore, no stable pair of distributions assigns positive probability to beliefs below $1-\epsilon$. □

Comment: The same argument as in the proof of Claim 2 implies that if all agents use the Min procedure, then in each state a distribution is stable if and only if it assigns probability equal to zero to any belief strictly above ϵ. It is also easy to verify that if all agents use the M^c procedure, then the only stable distribution will be concentrated on the belief that the state is a and if all agents use the M procedure, then the only stable distribution will be concentrated on the belief that the state is b.

4. Voting: An example

In models with incomplete information, agents aggregate multiple signals that are either observed privately and directly or inferred from the equilibrium. In this section, we present a simple example of strategic voting that illustrates the aggregation of private and equilibrium signals using some of the procedures discussed in the introduction.

Two jurors must determine the guilt of a defendant. Initially, they believe that the probability of the accused being guilty is $s = 0.1$. Each juror receives a conditionally independent binary signal about the guilt or innocence of the defendant which is incorrect with probability $\alpha = 0.1$. The jurors vote simultaneously on the defendant's guilt by choosing either Y or N. The defendant is found guilty only if both jurors vote Y.

The jurors' payoffs are depicted in the two matrices below: a juror receives 1 if the decision is correct when the defendant is guilty, 8 if the decision is correct when the defendant is innocent, and 0 in any other case. Thus, each juror prefers a conviction only if his belief that the defendant is innocent does not exceed 1/9.

Not Guilty	N	Y
N	8	8
Y	8	0

Guilty	N	Y
N	0	0
Y	0	1

Obviously, there is an equilibrium in which both jurors always vote N. If the jurors are Bayesian, then there is also an equilibrium in which they vote according to their signals. To see this, note that a juror cares only about the event in which he is pivotal, that is, when the other juror chooses Y. If he receives a signal declaring innocence and the other juror receives a signal declaring guilt (and thus votes Y), he believes that the defendant is guilty with probability $\frac{s(1-\alpha)\alpha}{(1-s)(1-\alpha)\alpha+s\alpha(1-\alpha)} = s = 0.1$ and it is indeed optimal for him to vote N. Conversely, with a signal declaring guilt, conditional on the other juror getting the same signal, the probability of guilt is $\frac{s(1-\alpha)^2}{s(1-\alpha)^2+(1-s)\alpha^2} = \frac{0.1(0.9)^2}{0.1(0.9)^2+0.9(0.1)^2} = 0.9$ and it is optimal for him to vote Y. Thus, voting Y if and only if the signal declares guilt is an equilibrium. A guilty defendant is convicted with probability 0.81 and an innocent one with probability 0.01.

Pivotal reasoning suggests a natural way of applying some of the non-Bayesian procedures we found in our survey. Assume that each juror forms his belief about the defendant's guilt by aggregating the beliefs from two signals: his own private signal and the "pivotal" event that the other agent votes Y. The latter signal is an "equilibrium" signal and its information content is determined by the equilibrium profile. Consider a profile in which the jurors vote according to their private signals. Each of the signals on its own increases the probability that the defendant is guilty to $\frac{s(1-\alpha)}{s(1-\alpha)+(1-s)\alpha} = 0.5$. Then, both the Avg and Max procedures generate the belief that the defendant is guilty with probability 0.5, while the M^c procedure generates the belief that the defendant is guilty with probability 0.75. Thus, on receiving a signal declaring guilt, a juror using any of those procedures will choose N. We conclude that such a profile is not an equilibirum and thus the unique equilibrium is non-informative.

In the next section we expand this example to a version of the familiar strategic voting game of Duggan and Martinelli (2001).

5. The voting game in Duggan and Martinelli (2001)

A panel of n jurors is to determine whether a defendant is guilty or innocent. The prior probability of guilt is denoted as s. The jurors vote simultaneously. Each juror votes either Y (guilty) or N (not guilty) and the defendant is found guilty only when the jurors unanimously vote Y. Prior to voting, each juror receives a private signal in the form of a number in $[0,1]$ about the guilt of the defendant and then votes whether or not to convict. The signals are identically distributed and conditionally independent across the jurors. The cdf of a signal conditional on the defendant being guilty (innocent) is F (G). The cdfs have continuous density functions f and g, respectively. The following restrictions are imposed throughout:[6]

[6] Condition (ii) implies that $\frac{F(t)}{G(t)} < \frac{f(t)}{g(t)} < \frac{1-F(t)}{1-G(t)}$ for all $t \in (0,1)$, $\frac{F(t)}{G(t)}$ and $\frac{1-F(t)}{1-G(t)}$ are strictly increasing, and together with (i), $\lim_{t\to 1} \frac{1-F(t)}{1-G(t)} = \infty$.

(i) $f(0) = 0$, $g(1) = 0$, $f(t) > 0$ for all $t > 0$ and $g(t) > 0$ for all $t < 1$.
(ii) $\frac{f(t)}{g(t)}$ is strictly increasing.

A juror prefers that the defendant be convicted if he believes that the probability of guilt is at least z, a number in $(0, 1)$. This is equivalent to each juror maximizing a vNM utility function that is equal to 1 if the correct decision is made when the defendant is guilty; it is equal to $\lambda = \frac{z}{1-z}$ if the correct decision is made when the defendant is innocent; and it is equal to 0 if the incorrect decision is made. Therefore, a natural welfare function when each juror votes Y if and only if his observed signal is at least α, is:

$$W^n(\alpha) = s(1 - F(\alpha))^n + (1 - s)\lambda(1 - (1 - G(\alpha))^n).$$

We assume that $z \geq 1/2 \geq s$. That is, the ex-ante belief that the defendant is guilty is not stronger than the belief that he is innocent and the standards for conviction are higher than the standards for acquittal.

In a strategic environment with incomplete information such as this one, the strategies of the "other players" generate events that can be interpreted by a player as "signals" and are aggregated with other exogenous signals to formulate posterior beliefs.[7] In the standard approach to binary voting models, a voter's best reply depends on his own information and the event in which his vote is pivotal. Accordingly, we assume that each juror aggregates two signals: his own private signal and the event that he is pivotal. The probability of guilt given the private signal is exogenous. The probability of guilt given that a juror is pivotal is determined in equilibrium. We assume that each juror applies a signal-aggregation procedure in order to form a belief about the defendant's guilt and votes to convict if the belief is above the threshold z.

We refer to juror i's belief that the defendant is guilty – given his private signal t and conditional on him being pivotal given that all players vote Y if and only if their signal is above σ – as his C-belief and denote it by $\mu_i(t, \sigma)$. The C-beliefs depend on the procedures – Bayesian or non-Bayesian – used by the jurors to update their beliefs.

To summarize, the model is the tuple $\langle n, s, z, F, G, (\mu_i)\rangle$ where n is the number of jurors, s is the common prior probability that the defendant is guilty, z is the common minimal belief as to the guilt of the defendant for which a conviction is optimal, F and G are the distributions of each private signal given that the defendant is respectively guilty or not guilty, and μ_i is juror i's C-belief.

It remains to define the equilibrium concept. A *(symmetric) equilibrium* is a cutoff $\sigma^* < 1$ such that for every juror i we have that $\mu_i(t, \sigma^*) \leq z$ for all $t < \sigma^*$ and $\mu_i(t, \sigma^*) \geq z$ for all $t > \sigma^*$. That is, in equilibrium whenever a juror votes N he believes that the probability of the defendant being guilty is sufficiently low (weakly below z) and whenever he votes Y he believes that it is sufficiently high (weakly above z). We require that $\sigma^* < 1$ in order to exclude the discussion of the non-informative equilibrium (which always exists) in which all players vote N regardless of their signals and no player is ever pivotal.

This model was not chosen because it is particularly realistic[8] but because it is simple and well known. Other applications could have served the same purpose. In models of mechanism design, auctions, bargaining, and pricing with rational expectations, agents also aggregate multiple "signals" that are either observed directly or inferred from equilibrium, as in the voting model.

We first review the voting model under the standard approach where for each i the C-beliefs are defined by Bayesian updating:

$$\mu_i(t, \sigma) = \frac{sf(t)(1 - F(\sigma))^{n-1}}{sf(t)(1 - F(\sigma))^{n-1} + (1 - s)g(t)(1 - G(\sigma))^{n-1}}.$$

Since μ_i is strictly increasing in t for a fixed $\sigma < 1$, σ^* is an equilibrium if and only if it satisfies:

$$\mu_i(\sigma^*, \sigma^*) = z.$$

Clearly, the equilibrium is unique.[9] For later use, we rearrange the equilibrium condition. Let $r^k(\theta)$ be the probability that the defendant is guilty conditional on k jurors with a common cutoff θ voting Y:

$$r^k(\theta) = \frac{s(1 - F(\theta))^k}{s(1 - F(\theta))^k + (1 - s)(1 - G(\theta))^k},$$

and set $r^k(1) = 1$, which is the limit of $r^k(\theta)$ as $\theta \to 1$. The function r^k is strictly increasing and $r^k(\theta) < r^{k+1}(\theta)$ for any $k \geq 1$ and $0 < \theta < 1$. Then, σ^* is an equilibrium if and only if it satisfies:

$$r^{n-1}(\sigma^*) = \frac{zg(\sigma^*)}{zg(\sigma^*) + (1 - z)f(\sigma^*)}.$$

It follows from Duggan and Martinelli (2001) that the equilibrium condition also characterizes welfare maximization with a common cutoff. As the number of jurors increases, the optimal cutoff decreases, converging to 0. Furthermore, the probability of an incorrect decision given the optimal cutoff also converges to 0. That is, the equilibrium level of welfare under the standard Bayesian approach converges to the "first-best", namely $s + (1 - s)\lambda$.

We now consider the case in which all or some of the players are non-Bayesian and use one of the procedures for signal aggregation described in the introduction. These procedures use a formula that is a function of the two probabilities of the relevant state conditional on each signal. In our case they are:

[7] For an alternative perspective on belief formation in Bayesian games, see Eyster and Rabin (2005).

[8] We agree with the criticism that the application of pivotal reasoning in voting is unrealistic (see Esponda and Vespa, 2014 for experimental evidence).

[9] Our assumptions imply that $\mu_i(0, 0) = 0$, and the function $\mu_i(t, t)$ is increasing, continuous and converges to 1 as $t \to 1$. Therefore, there is a unique α satisfying the equation $\mu_i(\alpha, \alpha) = z$.

(i) the probability $p(t)$ that the defendant is guilty given the juror's own signal t:

$$p(t) = \frac{sf(t)}{sf(t) + (1-s)g(t)};$$

(ii) the probability $r^{n-1}(\theta)$ that the defendant is guilty given that the juror is pivotal and the rest of the jurors use the cutoff θ.

Note that p is strictly increasing and satisfies $p(t) < r^k(t)$ for any $t \in (0,1)$ and $k \geq 1$.

We will see that replacing the Bayesian approach with other methods of signal aggregation (Avg or Max) discussed in the introduction yields significantly different results.

5.1. The Avg game

Assume that all jurors use the Avg procedure, that is, juror i's C-belief is:

$$\mu_i(t,\sigma) = \frac{1}{2}(p(t) + r^{n-1}(\sigma)).$$

Since C-beliefs are monotonic in t, the equilibria are characterized by the solutions of the equation $\frac{1}{2}(p(\beta) + r^{n-1}(\beta)) = z$. The following claim states that the equilibrium cutoff is above the Bayesian one and as the number of jurors increases the probability that any defendant is convicted converges to zero.

Claim 3. *In the Avg game:*
(i) There is a unique equilibrium denoted by β^*.
(ii) $\beta^* \geq \sigma^*$ with strict inequality unless $z = s = \frac{1}{2}$.
(iii) Denote by $\beta^*(n)$ the equilibrium in the game with n jurors. If $z > \frac{1}{2}$, then as $n \to \infty$:
(a) $\beta^*(n) \to \bar{\beta}$ where $p(\bar{\beta}) + 1 = 2z$; and
(b) the level of welfare converges to $\lambda(1-s)$ (the defendant is almost never convicted).

Proof. (i) The function $\frac{1}{2}(p(\beta) + r^{n-1}(\beta))$ is increasing in β and ranges from $\frac{s}{2}$ to 1. Hence there is a unique β^* at which it equals z. Clearly, this is the unique equilibrium.
(ii) Since $z \geq s$:

$$p(\sigma^*) + r^{n-1}(\sigma^*) = \frac{sf(\sigma^*)}{sf(\sigma^*) + (1-s)g(\sigma^*)} + \frac{zg(\sigma^*)}{zg(\sigma^*) + (1-z)f(\sigma^*)} \leq$$
$$\frac{zf(\sigma^*)}{zf(\sigma^*) + (1-z)g(\sigma^*)} + \frac{zg(\sigma^*)}{zg(\sigma^*) + (1-z)f(\sigma^*)} \leq 2z.$$

The first inequality holds strictly unless $s = z = \frac{1}{2}$ given that $z \geq \frac{1}{2} \geq s$. The second inequality follows from $\frac{x}{zx+(1-z)y} + \frac{y}{zy+(1-z)x} \leq 2$ which holds with equality only for $z = \frac{1}{2}$ or $x = y$(or $z = 1$). Therefore, one of the inequalities will hold strictly unless $s = z = \frac{1}{2}$. By the monotonicity of p and r^{n-1}, it follows that $\beta^* \geq \sigma^*$ with strict inequality unless $z = s = \frac{1}{2}$.
(iii) Since the function $\frac{1}{2}(p(\beta) + r^{n-1}(\beta))$ is increasing in β and n, the sequence $\beta^*(n)$ is decreasing. Since $p(\beta^*(n)) \geq 2z - 1 > 0$, $\beta^*(n)$ is bounded away from 0 and the equilibrium probability that the defendant will be found guilty converges to 0 as $n \to \infty$. Therefore, the sequence $\beta^*(n)$ converges to the unique solution of $p(\beta) + 1 = 2z$. □

5.2. The Max game

Suppose that all the jurors use the Max procedure, that is, for all i:

$$\mu_i(t,\theta) = max\{p(t), r^{n-1}(\theta)\}.$$

The following claim states that the equilibrium cutoff is always below the Avg cutoff and also below the Bayesian one when n is large. As the number of jurors increases, the equilibrium level of welfare approaches that in the Avg game, namely the level of welfare in the case of a panel of jurors that never convicts, despite the fact that convictions occur with probability larger than s.

Claim 4. *In the Max game:*
(i) There exists a unique equilibrium γ^* satisfying $r^{n-1}(\gamma^*) = z$.
(ii) $\gamma^* \leq \beta^*$.
(iii) Let $\gamma^*(n)$ be the equilibrium in the game with n jurors. There exists a sequence $\eta(n)$ that converges to ∞ such that for any n, $\sigma^*(n) > \gamma^*(n)$ if and only if $\lambda < \eta(n)$.
(iv) As n increases, the probability of convicting a guilty defendant converges to 1 and that of convicting an innocent one converges to $\frac{s}{(1-s)\lambda}$. The level of welfare converges to $\lambda(1-s)$.

Proof. (i) The unique solution γ^* of $r^{n-1}(\gamma) = z$ is an equilibrium: if a juror receives a signal below γ^*, then his C-belief is z and he is indifferent between voting Y and voting N; if he receives a signal above γ^*, then his C-belief is at least z and voting Y is optimal.

There is no other equilibrium:
(a) A common cutoff $\underline{\gamma} < \gamma^*$ is not an equilibrium since a juror with a signal $t \in (\underline{\gamma}, \gamma^*)$ has a C-belief equal to $max\{p(t), r^{n-1}(\underline{\gamma})\}$ which

is less than z since $p(t) < p(\gamma^*) < r^{n-1}(\gamma^*) = z$ and $r^{n-1}(\underline{\gamma}) < r^{n-1}(\gamma^*) = z$. Such a juror prefers to vote N.
(b) A common cutoff $\bar{\gamma} > \gamma^*$ is not an equilibrium since in that case any juror's C-belief is at least $r^{n-1}(\bar{\gamma}) > z$ and thus voting N is not optimal given any signal.

(ii) The assertion follows from the Avg equilibrium condition $\frac{1}{2}(p(\beta^*) + r^{n-1}(\beta^*)) = z$ and the fact that $r^{n-1}(t) > p(t)$ for all $t \in (0,1)$.
(iii) $\gamma^*(n)$ is the solution to $\frac{r^{n-1}(t)}{1-r^{n-1}(t)} = \lambda$ and $\sigma^*(n)$ is the solution to $\frac{r^{n-1}(t)}{1-r^{n-1}(t)}\frac{f(t)}{g(t)} = \lambda$. The two LHS functions are increasing and have the same value only at the point $\bar{t}$ such that $f(\bar{t}) = g(\bar{t})$. Define $\eta(n) = \frac{r^{n-1}(\bar{t})}{1-r^{n-1}(\bar{t})}$. The sequence converges to infinity since $F(\bar{t}) < G(\bar{t})$. Then, $\lambda < \eta(n)$ iff $\gamma(n) < \bar{t}$ iff $\frac{f(\gamma(n))}{g(\gamma(n))} < 1$ iff $\sigma^*(n) > \gamma^*(n)$.
(iv) Since $\gamma^*(n) < \sigma^*(n)$ for large n, the probability that a guilty defendant is found guilty goes to 1. The ratio of convictions of guilty defendants to those of innocent defendants is $\frac{s(1-F(\gamma^*(n)))^n}{(1-s)(1-G(\gamma^*(n)))^n} = \frac{r^{n-1}(\gamma^*(n))}{1-r^{n-1}(\gamma^*(n))}\frac{1-F(\gamma^*(n))}{1-G(\gamma^*(n))}$ which converges to λ by the equilibrium condition. Therefore, the probability of an innocent defendant being found guilty converges to $\frac{s(1-z)}{(1-s)z}$ and the level of welfare converges to $s + (1-s)\lambda(1 - \frac{s}{1-s}\frac{1-z}{z}) = \lambda(1-s)$. □

Comment (the Min Game): By an argument similar to that in Claim 4, the only equilibrium of the game in which all the jurors follow the Min procedure is δ^* satisfying $p(\delta^*) = z$. Since the equilibrium is independent of n and $\delta^* > 0$, the probability of conviction goes to zero as the number of jurors increases, and the level of welfare converges to $(1-s)\lambda$, as in the Avg and Max games.

Comment (the Mixed Bayesian and *Avg* Game): Suppose that $n\kappa$ jurors are Bayesian and the rest (at least two) use Avg. An extension of the equilibrium definition specifies α^* and β^* (both less than 1) where α^* is the common cutoff of the Bayesian players and β^* is the common cutoff of the Avg players. Assume that $z > \frac{1}{2} > s$. The following claim shows that an equilibrium exists and that the equilibrium probability of conviction converges to zero as n increases.

Claim 5. *Suppose that $z > \frac{1}{2} > s$.*[10] *Then:*
(i) An equilibrium exists.
(ii) Any sequence of equilibria $(\alpha^*(n), \beta^*(n))$ converges to $(0, \bar{\beta})$ where $p(\bar{\beta}) = 2z - 1$ and the equilibrium probability of conviction converges to zero as $n \to \infty$.

Proof.
(i) Define $\psi(t) = \frac{1-G(t)}{1-F(t)}$. An equilibrium $(\alpha^*, \beta^*) \in (0,1) \times (0,1)$ is characterized as a solution of the equations:

$$\frac{1}{1 + \frac{1-s}{s}\frac{g(\alpha)}{f(\alpha)}(\psi(\alpha))^{\kappa n-1}(\psi(\beta))^{n-\kappa n}} = z$$
$$\frac{1}{2}[p(\beta) + \frac{1}{1 + \frac{1-s}{s}(\psi(\alpha))^{\kappa n}(\psi(\beta))^{n-\kappa n-1}}] = z.$$

A solution in $(0,1) \times (0,1)$ exists.[11]
(ii) Let $(\alpha^*(n), \beta^*(n))$ be a sequence of equilibria. The sequence $\alpha^*(n)$ converges to 0. If not, there would be an $\epsilon > 0$ and a subsequence that is above ϵ. Since $\psi(\epsilon) \in (0,1)$ and ψ is increasing, the LHS of the first equation along the subsequence would converge to $1 > z$.

Since $p(\beta^*(n)) > 2z - 1 > 0$ there is $\epsilon > 0$ such that $\beta^*(n) > \epsilon$ for all n. Since $\psi(\epsilon) \in (0,1)$, by the second equation $\beta^*(n)$ converges to $\bar{\beta}$, the unique solution of $p(\beta) = 2z - 1$ and $\beta^*(n) > \bar{\beta}$. It follows that the probability that all Avg jurors will vote Y is less than $s(1 - F(\bar{\beta}))^{n(1-\kappa)} + (1-s)(1 - G(\bar{\beta}))^{n(1-\kappa)}$, which converges to zero as $n \to \infty$. □

Comment (Aggregation of n Signals): An alternative approach to modelling belief formation with non-Bayesian procedures is that each juror aggregates n signals rather than just two: his own signal and additional distinct signals, one for each Y vote cast by the other jurors. That is, a juror i who receives the signal t and knows that all of the other jurors follow a common cutoff θ forms his C-belief by aggregating:
(i) his own signal t (according to which the defendant is guilty with probability $p(t)$); and
(ii) $n-1$ other signals: for each juror $j \neq i$ the signal that he is voting Y, that is, j's private signal, is at least θ (for any one of these signals the defendant is guilty with probability $r^1(\theta)$).
Thus, under the Avg approach, $\mu_i(t,\theta) = \frac{1}{n}(p(t) + (n-1)r^1(\theta))$ and under the Max approach, $\mu_i(t,\theta) = max\{p(t), r^1(\theta)\}$.

We verified that the conclusions reached in this section remain essentially valid under this approach. In particular, in the equilibria of the Avg and Max games, the probability of conviction goes to zero as the number of jurors becomes large.

[10] When $s = z = \frac{1}{2}$ there exists an equilibrium that is identical to the one in which all n players are Bayesian (or use Avg). Let τ^* be the solution of the equation $\frac{g(\tau)}{f(\tau)}(\psi(\tau))^{n-1} = 1$. Then, τ^* also solves the equation $p(\tau) + 1/(1 + (\psi(\tau))^{n-1}) = 1$. Therefore, $\alpha^* = \beta^* = \tau^*$ is an equilibrium. Obviously, τ^* is also an equilibrium when all jurors are either Bayesian or use Avg.

[11] For every $\beta < 1$, there is a unique $\alpha \in [0,1)$ that solves the first equation since the equation's LHS converges to 0 as $\alpha \to 0$ and to 1 as $\alpha \to 1$. Denote this solution by $a(\beta)$. For every $\alpha \in [0,1]$, there is a unique $\beta \in (0,1)$ which solves the second equation since the LHS converges to 1 as $\beta \to 1$ and is equal to $\frac{1}{2(1+\frac{1-s}{s}(\psi(\alpha))^{\kappa n})} < \frac{1}{2}$ at $\beta = 0$. Denote this solution by $b(\alpha)$. The functions $a(\beta)$ and $b(\alpha)$ are continuous and decreasing. It can easily be verified using standard arguments that there exists $(\alpha^*, \beta^*) \in (0,1) \times (0,1)$ which solves both equations.

6. Final discussion

The basic puzzle: One of the main contributions of this paper is a "practical" one: when processing conditional independent signals using the Bayesian paradigm, two relatively weak signals that a rare state has been realized can be combined to produce very strong evidence. The fact that people fail to recognize that two moderate and conditionally independent signals of a rare event aggregate to significant evidence for the event was confirmed not only in our survey but also in discussions with colleagues familiar with probability theory, many of whom – like us – were surprised by this feature of Bayesian updating. This informal evidence is unambiguously the main motivation for the paper.

The economics message: Individuals often use non-Bayesian procedures to process multiple signals based on simple intuitive formulae. We showed that replacing Bayesian agents with agents who follow one of these alternatives can have a significant effect on the equilibrium analysis in standard economic models.

Acknowledgment of weaknesses:[12] a. We acknowledge a gap between the theoretical models and the framework of the experiments. In both theoretical models, the two signals aggregated by the agents contain different types of information: one is an exogenous private signal and the other is an endogenous signal (a sample signal in the model of opinion formation and strategically inferred information in the voting game). In the survey experiment, the two signals are instead derived from similar tests and thus likely to trigger the use of symmetric aggregation rules. It is possible (see Andreoni and Mylovanov, 2012) that asymmetries in the nature of the signals could result in rules for signal aggregation that differ from the ones that identified in the survey.

b. It is natural to expect aggregation rules to be context-dependent. For example, Budescu and Yu (2006) found that the choices of subjects in their experiment were more in line with the naive Bayes rule than the simple averaging rule when signals were extreme and highly consistent with each other. Mislavsky and Gaertig (2021) showed that, qualitatively, for verbal probabilities aggregation is more consistent with Bayesian updating.

c. In any realistic context it is also reasonable to expect a significant degree of heterogeneity in the updating methods used by subjects. However, for analytical reasons, our theoretical analysis focuses, with one exception, on replacing Bayesian updating with a homogenous alternative rule.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declares that they have no relevant or material financial interests that relate to the research described in this paper.

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[12] We thank a referee of this journal for bringing points (a) and (b) to our attention.