Theory Dec.
DOI 10.1007/s11238-013-9362-7

On the significance of the prior of a correct decision in committees

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Abstract The current note clarifies why, in committees, the prior probability of a correct collective choice might be of particular significance and possibly should sometimes even be the sole appropriate basis for making the collective decision. In particular, we present sufficient conditions for the superiority of a rule based solely on the prior relative to the simple majority rule, even when the decisional skills of the committee members are assumed to be homogeneous.

Keywords Committee · Optimal decision rule · Majority rule · Prior-based rule

1 Introduction

The motivation behind CJT, Condorcet (1785), namely the pioneering formal "rational" justification of democracy based on majority rule, implies that Condorcet had large bodies of voters in mind. The assumptions of the theorem, which focuses on the simple majority rule and homogeneous decisional capabilities, directly entail that the prior of the correct collective decision (henceforth, the prior) and the particular decisional skills of the voters as well as the possibility of strategic behavior were disregarded. These explicit assumptions are plausible when one tries to argue for the support of democracy in large voting bodies. The reason is that in such cases, CJT makes the crucial point that general voter participation ensures an almost certain correct collective choice.

By our main result, an estimate of the relationship between the prior and the individual decisional skill might be sufficient to determine that the prior-based rule (PBR) is superior to the simple majority rule (SMR), in committees. If the ratio between the

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Published online: 23 March 2013

prior and the voters' identical decisional skills is larger than 1, then the prior should be taken into account, which means that SMR is not the optimal decision rule.[1] If the ratio is sufficiently large, then reliance just on the prior might be justified, which means that the committee members' decisions should not be taken into account. If the ratio between the prior and the individual decisional capability is sufficiently large, then reliance on a PBR, even when it is not optimal, is superior to the use of the non-optimal SMR. This superiority is valid despite the homogeneity of decisional capabilities and even for non-informative decisions.

2 The setting

There are $n = 2k + 1$ individuals in a decision-making group N, $N = \{1, \ldots, n\}$. In our uncertain environment, there are two possible states of nature that are denoted 1 and -1. Assume that state of nature 1 has a prior probability α, $0 < \alpha < 1$. The group has to make a choice between two alternatives 1 and -1, one of which, the correct one, is preferred by all the individuals in the group.[2] Alternative 1 is correct in state of nature 1 and alternative -1 is correct in state of nature -1. The identity of the preferred alternative is, however, unknown because of the uncertainty regarding the realized state of nature. Before the committee reaches its decision, each of its members i observes a random private signal, which is either 1 or -1. The signals, which are assumed to be independent, represent the members' opinions regarding the preferred collective decision. The opinions are based on the individuals' private information, life experience and expertise. As in the setting of the seminal CJT and some of the recent related studies, e.g., Austen-Smith and Banks (1996) and Feddersen and Pesendorfer (1998), we make simple assumptions about the signals. In particular, we assume that the voters are homogeneous and capable. That is, they share an identical probability p of observing the signal $1(-1)$ in state of nature $1(-1)$, $p > 1/2$.[3] This probability, which is referred to as the individual decisional skill to make the correct decision, is independent of the state of nature. After the signals are observed, the committee members take a vote. Each committee member i must vote either 1 or -1. A voting strategy for individual i is a rule that determines his vote x_i as a function of his private signal. If this function is the identity function (his vote is identical to his signal), then the individual is said to vote informatively. Otherwise, the individual votes non-informatively. The final collective decision is made using a decision rule f that assigns 1 or -1 to any decision or voting profile $x = (x_1, \ldots, x_n)$. Under our symmetry assumption that the net benefit from a

[1] The general uncertain dichotomous choice model can be used to study optimal informative voting in any voting body, Baharad et al. (2011, 2012); Ben-Yashar and Danziger (2011); Ben-Yashar and Kraus (2002); Ben-Yashar and Nitzan (1997); Nitzan (2010); Nitzan and Paroush (1982, 1985); Nurmi (2002); Shapley and Grofman (1984); Young (1995). Here both decisional skills and the prior of a correct collective decision are explicitly taken into account and, of course, the optimal rule need not be the SMR.

[2] The classical social choice problems due to the existence of heterogeneous preferences, e.g., the problem of majority tyranny, Baharad and Nitzan (2002) or the difficulty of attaining a reasonable social compromise, Young (1988, 1995), can be disregarded in our setting.

[3] CJT can be generalized to the case of heterogeneous voters. See, for example, Ben-Yashar and Zahavi (2011); Berend and Paroush (1998); Berend and Sapir (2005).

correct decision is equal under the two possible states of nature, the group objective of maximizing its expected benefit is equivalent to the objective of maximizing the probability of making a correct collective decision. By the main result in Nitzan and Paroush (1982) and Ben-Yashar and Nitzan (1997), if individuals have an identical decisional skill p, the optimal decision rule f^* can be written as: $f^* = sign(\sum_{i=1}^{n} wx_i + \gamma)$, where $sign(m) = \begin{cases} 1 & m > 0 \\ -1 & \text{otherwise} \end{cases}$, $w = \ln \frac{p}{1-p}$ and $\gamma = \ln \frac{\alpha}{1-\alpha}$. This rule is a qualified majority rule (QMR). Each such rule corresponds to an integer q, the quota required for the collective decision to be 1. That is, the collective decision is 1, if and only if the number of supporters of 1 is larger than or equal to q. If $q \leq 0$ or $q \geq n + 1$, then the QMR is an extreme constant rule because the collective decision is always, respectively, 1 or -1, regardless of the votes. With no loss of generality, suppose that $\alpha > 1/2$. In such a case, the QMR with a quota $q \leq 0$ is called PBR, f^{PBR}. If $q = k+1$, then the collective decision rule is the SMR, f^{SMR}.

3 The significance of the prior in committees

The importance of the prior of a correct collective decision is a straightforward corollary of the result identifying the optimal decision rule f^*. As indicated, the optimal decision rule depends on the prior and the individual decisional skills, where γ represents the prior α, $\gamma \geq 0 \Leftrightarrow \alpha \geq 1/2$. The optimal weight of an individual's decision is w, $w \geq 0 \Leftrightarrow p \geq 1/2$. The relationship between γ and w determines the optimal decision rule. Specifically, if $\frac{\gamma}{w} > 1$, i.e., $\alpha > p$, then the SMR is not the optimal decision rule.[4]

[4] *Proof*: As noted above,

$$f^* = sign\left(\sum_{i=1}^{n} wx_i + \gamma\right)$$

The SMR is defined as follows:

$$f^{SMR} = sign\left(\sum_{i=1}^{n} x_i\right)$$

Therefore, the SMR is optimal if

$$\forall x \left(\sum_{i=1}^{n} wx_i + \gamma > 0 \Leftrightarrow \sum_{i=1}^{n} x_i > 0\right)$$

Notice that for x such that the number of supporters in alternative 1 is $\frac{n-1}{2}$, If $\frac{\gamma}{w} > n$,i.e., $\frac{\alpha}{1-\alpha} > \left(\frac{p}{1-p}\right)^n$, then reliance solely on the prior, that is, using the PBR, is optimal. [5] Clearly, the effect of the prior is stronger, the smaller the number of decision makers. The SMR can be inferior relative to the PBR, even when the latter is *not* the optimal decision rule.

Theorem 1 *A necessary and sufficient condition for the PBR to be superior to the SMR is:*$\gamma > (k+1)w + \ln A$, *where*

$$A = \frac{\sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^{i-(k+1)}(1-p)^{2k+1-i}}{\sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^{2k+1-i}(1-p)^{i-(k+1)}}$$

A sufficient condition for the superiority of the PBR relative to the SMR is: $\frac{\gamma}{w} > k+1$.

Proof Let π^{PBR}, π^{SMR} and π^* denote, respectively, the probability of making the correct collective choice under the PBR, SMR and the optimal QMR. By definition, $\pi^* \geq \pi^{\text{PBR}}$ and $\pi^* \geq \pi^{\text{SMR}}$. We have to provide the condition ensuring that

$$\pi^* - \pi^{\text{PBR}} < \pi^* - \pi^{\text{SMR}} \Leftrightarrow \pi^{\text{PBR}} > \pi^{\text{SMR}}$$

For any decision rule f, the probability of making the correct collective choice is given by (see Nitzan and Paroush 1982 and Ben-Yashar and Nitzan 1997):

$$\pi^f = \alpha\pi^f(1/1) + (1-\alpha)\pi^f(-1/-1),$$

where $\pi^f(1/1)$ and $\pi^f(-1/-1)$ are the probabilities of making the correct collective choice in state of nature 1 and -1.

Notice that since $\alpha > 1/2$, the collective decision under the PBR is always 1 and, therefore,

Footnote 4 continued

$$f^* = sign\left(\left(\frac{n-1}{2} - \frac{n+1}{2}\right)\ln\frac{p}{1-p}\right) + \ln\frac{\alpha}{1-\alpha}\right) = sign\left(-\ln\frac{p}{1-p} + \ln\frac{\alpha}{1-\alpha}\right) = 1,$$

since, by assumption, $\alpha > p$.

$$f^{\text{SMR}} = sign\left(\frac{n-1}{2} - \frac{n+1}{2}\right) = -1.\text{That is, } f^* \neq f^{\text{SMR}}.$$

□

[5] *Proof*: Note that when $\alpha > 1/2$, $f^{\text{PBR}} = 1$.

$f^* = f^{\text{PBR}} = 1, if \forall x,$

$\sum_{i=1}^{n} wx_i + \gamma > 0$, and this is true for every x, in particular, even for $x = (-1, -1, -1, \ldots, -1)$. This means that $\gamma - nw > 0 \Leftrightarrow \ln\frac{\alpha}{1-\alpha} > n\ln\frac{p}{1-p} \Leftrightarrow \frac{\alpha}{1-\alpha} > (\frac{p}{1-p})^n$. □

$$\pi^{\text{PBR}}(1/1) = \sum_{i=0}^{2k+1} \binom{2k+1}{i} p^i (1-p)^{2k+1-i}$$

$$\pi^{\text{PBR}}(-1/-1) = 0$$

and

$$\pi^{\text{SMR}}(1/1) = \pi^{SMR}(-1/-1) = \sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^i (1-p)^{2k+1-i}$$

Hence,

$$\begin{aligned}
&\pi^{\text{PBR}} > \pi^{\text{SMR}} \\
&\Leftrightarrow \alpha \sum_{i=0}^{2k+1} \binom{2k+1}{i} p^i (1-p)^{2k+1-i} > (\alpha + 1-\alpha) \sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^i (1-p)^{2k+1-i} \\
&\Leftrightarrow \alpha \sum_{i=0}^{k} \binom{2k+1}{i} p^i (1-p)^{2k+1-i} + \alpha \sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^i (1-p)^{2k+1-i} \\
&\quad > \alpha \sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^i (1-p)^{2k+1-i} + (1-\alpha) \sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^i (1-p)^{2k+1-i}
\end{aligned}$$

Since $\sum_{i=0}^{k} \binom{2k+1}{i} p^i (1-p)^{2k+1-i} = \sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^{2k+1-i} (1-p)^i$, the latter inequality can be rewritten as:

$$\alpha \sum_{i=k+1}^{2k+1} \binom{2k+1}{i} (1-p)^i p^{2k+1-i} > (1-\alpha) \sum_{i=k+1}^{2k+1} \binom{2k+1}{i} (1-p)^{2k+1-i} p^i$$

We have therefore obtained that

$$\pi^{\text{PBR}} > \pi^{\text{SMR}} \Leftrightarrow \frac{\alpha}{1-\alpha} > \frac{\sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^i (1-p)^{2k+1-i}}{\sum_{i=k+1}^{2k+1} \binom{2k+1}{i} p^{2k+1-i} (1-p)^i}$$

That is,

$$\pi^{PBR} > \pi^{SMR} \Leftrightarrow \frac{\alpha}{1-\alpha} > \frac{p^{k+1}\sum_{i=k+1}^{2k+1}\binom{2k+1}{i}p^{i-(k+1)}(1-p)^{2k+1-i}}{(1-p)^{k+1}\sum_{i=k+1}^{2k+1}\binom{2k+1}{i}p^{2k+1-i}(1-p)^{i-(k+1)}}$$

$$\Leftrightarrow \gamma > (k+1)w + \ln A$$

where $A = \frac{\sum_{i=k+1}^{2k+1}\binom{2k+1}{i}p^{i-(k+1)}(1-p)^{2k+1-i}}{\sum_{i=k+1}^{2k+1}\binom{2k+1}{i}p^{2k+1-i}(1-p)^{i-(k+1)}}$.

We now have to show that A is smaller than 1. In turn, ln A is negative and, consequently, $\gamma > (k+1)w$ is a sufficient condition for the superiority of the PBR over the SMR.

$$A = \frac{\sum_{i=k+1}^{2k+1}\binom{2k+1}{i}p^{i-(k+1)}(1-p)^{2k+1-i}}{\sum_{i=k+1}^{2k+1}\binom{2k+1}{i}p^{2k+1-i}(1-p)^{i-(k+1)}} < 1$$

$$\Leftrightarrow \sum_{i=k+1}^{2k+1}\binom{2k+1}{i}\left[p^{i-(k+1)}(1-p)^{2k+1-i} - p^{2k+1-i}(1-p)^{i-(k+1)}\right] < 0$$

$$\Leftrightarrow \sum_{t=0}^{k}\binom{2k+1}{k+1+t}(p^t(1-p)^{k-t} - p^{k-t}(1-p)^t) < 0$$

$$\Leftrightarrow \sum_{t=0}^{\left\lfloor\frac{k-1}{2}\right\rfloor}\left[\binom{2k+1}{k+1+t} - \binom{2k+1}{2k+1-t}\right](p^t(1-p)^{k-t} - p^{k-t}(1-p)^t) < 0$$

Let us prove that the latter inequality is always satisfied.

Case 1: Suppose that $k > 2t \Leftrightarrow k-t > t$

In this case, $(p^t(1-p)^{k-t} - p^{k-t}(1-p)^t) < 0$ and $\binom{2k+1}{k+1+t} - \binom{2k+1}{2k+1-t} > 0$.

Case 2: Suppose that $k < 2t \Leftrightarrow k-t < t$

In this case, $(p^t(1-p)^{k-t} - p^{k-t}(1-p)^t) > 0$ and $\binom{2k+1}{k+1+t} - \binom{2k+1}{2k+1-t} < 0$.

Notice that for $k = 2t \Leftrightarrow k-t = t$, $(p^t(1-p)^{k-t} - p^{k-t}(1-p)^t) = 0$.

We therefore get that the inequality is satisfied. □

When $\frac{\gamma}{w} < 1$, the SMR is the optimal decision rule and the condition in Theorem 1 is not satisfied. When $\frac{\gamma}{w} > n$, the PBR is optimal, so in particular, it is superior to the SMR. When $1 < \frac{\gamma}{w} \leq n$, neither of these rules is optimal. In such a case the condition $\frac{\gamma}{w} > k + 1$ ensures that the PBR is preferred to the SMR.

3.1 Single-peakedness

Our analysis implies that the performance of the relevant potentially optimal decision rules is single peaked. These rules are ordered along the spectrum from the extreme PBR to the extreme SMR. In the former case, no voter's support is needed to make the collective decision. The prior determines the decision of the committee. In the latter case, the decision of the committee requires the support of at least $(k + 1)$ voters. The non-extreme intermediate rules require the support of just t voters, where t varies from 1 to k, to choose the alternative preferred according to the prior. These intermediate rules can be interpreted as QMR's. Single-peakedness is satisfied because, given the above order of the decision rules, any deviation from the optimal (extreme or non-extreme) decision rule (any decrease or increase in the optimal required majority) reduces the probability that the committee makes the correct decision. In particular, when the PBR is optimal, the SMR is the worst decision rule. By Theorem 1, if the optimal rule is an intermediate QMR and $\frac{\gamma}{w} > k + 1$, then the probability of a correct collective decision under the PBR is larger than under the SMR. In any event, in the absence of information on the optimal decision rule, one cannot argue that the SMR has an advantage relative to the PBR.

3.2 Non-informative voting

When the applied rule is a SMR which is not optimal, the voters have an incentive to vote non-informatively. That is, one or more committee members vote non-informatively to increase the probability of making a correct collective decision, assuming that all other members vote informatively, Austen-Smith and Banks (1996); McLennan (1998). In such a case, the optimal QMR under non-informative voting is the same as the optimal rule under informative voting, Ben-Yashar and Milchtaich (2007). The optimality of SMR, therefore, requires that $\alpha < p$. If this inequality is not satisfied and SMR is used, informative voting is not a Nash equilibrium, and since $\alpha > 1/2$, the only relevant strategic voting for an individual member is to disregard his private information and always vote +1. A strategic voting has the potential to increase the probability of making a correct collective decision beyond that obtained under informative voting. A committee member voting strategically affects the collective probability only when he is pivotal, that is, under SMR, when his private information is -1, k members vote +1 and k members vote -1. This implies that in state of nature +1, the collective probability is increased by $\binom{2k}{k} p^k (1-p)^{k+1}$ and in state of nature -1 the collective probability is reduced by $\binom{2k}{k} p^{k+1} (1-p)^k$.

Hence the expected change is $\alpha \binom{2k}{k} p^k(1-p)^{k+1} - (1-\alpha)\binom{2k}{k} p^{k+1}(1-p)^k = \binom{2k}{k} p^k(1-p)^k(\alpha - p)$. Assuming that $\alpha > p$, this difference is positive. [6] We therefore get that, under SMR and non-informative voting, the probability of making a correct choice is:

$$\alpha\pi^{\text{SMR}}(1/1) + (1-\alpha)\pi^{\text{SMR}}(-1/-1) + \binom{2k}{k} p^k(1-p)^k(\alpha - p).$$

The result that if the ratio between the prior and the individual decisional capability is sufficiently large, then reliance on a PBR, even when it is not optimal, is superior to the use of the non-optimal SMR is also valid, albeit with a stronger condition, when strategic voting is allowed.

Theorem 2 *Under strategic voting, a necessary condition for the PBR to be superior to the SMR is:*$\gamma > (k+1)w + \ln(A+B)$,

$$\textit{where } B = \frac{\binom{2k}{k}(1-p)^k \frac{\alpha-p}{p(1-\alpha)}}{\sum_{i=k+1}^{2k+1}\binom{2k+1}{i} p^{2k+1-i}(1-p)^{i-(k+1)}}$$

Proof

$$\alpha > \alpha\pi^{\text{SMR}}(1/1) + (1-\alpha)\pi^{\text{SMR}}(-1/-1) + \binom{2k}{\text{k}} p^k\,(1-p)^k\,(\alpha - p)$$

$$\Leftrightarrow \alpha \sum_{i=k+1}^{2k+1}\binom{2k+1}{i}(1-p)^i p^{2k+1-i} > (1-\alpha)\sum_{i=k+1}^{2k+1}\binom{2k+1}{i}(1-p)^{2k+1-i} p^i + \binom{2k}{\text{k}} p^k\,(1-p)^k\,(\alpha - p)$$

We have therefore obtained that

$$\pi^{\text{PBR}} > \pi^{\text{SMR}}$$

$$\Leftrightarrow \frac{\alpha}{1-\alpha} > \frac{\sum_{i=k+1}^{2k+1}\binom{2k+1}{i} p^i(1-p)^{2k+1-i} + \binom{2k}{\text{k}} p^k\,(1-p)^k\,\frac{\alpha-p}{(1-\alpha)}}{\sum_{i=k+1}^{2k+1}\binom{2k+1}{i} p^{2k+1-i}(1-p)^i}$$

[6] For larger committees, more individuals are required to vote non-informatively to increase the probability of making the correct collective decision. In the extreme case where the PBR is the optimal rule, non-informative voting by the majority of the committee members can lead to the attainment of the maximal performance (the highest possible probability of making the correct collective choice). Clearly, strategic voting by an individual committee member is less effective than strategic voting by a subgroup of the committee members.

That is,

$$
\begin{aligned}
&\pi^{\mathrm{PBR}} > \pi^{\mathrm{SMR}} \\
&\Leftrightarrow \frac{\alpha}{1-\alpha} > \frac{p^{k+1}\left[\sum_{i=k+1}^{2k+1}\binom{2k+1}{i}p^{i-(k+1)}(1-p)^{2k+1-i}+\binom{2k}{\mathrm{k}}(1-p)^{k}\,\frac{\alpha-p}{p(1-\alpha)}\right]}{(1-p)^{k+1}\sum_{i=k+1}^{2k+1}\binom{2k+1}{i}p^{2k+1-i}(1-p)^{i-(k+1)}} \\
&\Leftrightarrow \gamma > (k+1)w+\ln(A+B)
\end{aligned}
$$

□

In a three-member committee,$n = 3$, $\alpha > 1/2$, there are just three potentially optimal decision rules: the PBR, the rule requiring the support of just a single voter in the alternative supported by the prior and the SMR. Note that the intermediate rule is also a QMR, such that, a collective decision in favor of the alternative not supported by the prior requires unanimous support. In this case the PBR is preferred to the SMR under informative and non-informative voting provided that $\frac{\gamma}{w} > 2$.

$$
\begin{aligned}
&\pi^{\mathrm{PBR}} > \pi^{\mathrm{SMR}}+2p(1-p)(\alpha-p) \\
&\Leftrightarrow \alpha > \alpha(p^3+3p^2(1-p)+2p(1-p)^2)+(1-\alpha)(p^3+3p^2(1-p)-2p^2(1-p)) \\
&\Leftrightarrow \alpha > \alpha(1-(1-p)^3-p(1-p)^2-p^3-p^2(1-p))+p^3+p^2(1-p) \\
&\Leftrightarrow \alpha > \alpha(2p(1-p)^2+2p^2(1-p))+p^2 \\
&\Leftrightarrow \alpha(1-p)^2 > (1-\alpha)p^2 \Leftrightarrow \gamma > 2w,
\end{aligned}
$$

Note that in a committee with more than 3 members, the expected advantage due to non-informative voting by an individual, $\binom{2k}{k}p^k(1-p)^k(\alpha-p)$, is decreasing with k, because the probability of being pivotal decreases with k.[7]

[7] This advantage is decreasing with k because

$$
\begin{aligned}
&\binom{2(k+1)}{k+1}p^{k+1}(1-p)^{k+1}(\alpha-p)-\binom{2k}{k}p^{k}(1-p)^{k}(\alpha-p)<0\Leftrightarrow \\
&\binom{2k}{k}p^{k}(1-p)^{k}(\alpha-p)(\tfrac{(2k+1)(2k+2)}{(k+1)(k+1)}p(1-p)-1)<0\Leftrightarrow \\
&\binom{2k}{k}p^{k}(1-p)^{k}(\alpha-p)(\frac{(2k+1)2p(1-p)-(k+1)}{(k+1)}<0\Leftrightarrow \\
&2p(1-p)<\tfrac{k+1}{2k+1}.
\end{aligned}
$$

3.3 Cursory empirical evidence

On the one hand, in many contexts, a committee facing an uncertain dichotomous choice problem can use a relatively high prior α. Such a case is reported in Koppel et al. (2012) who study the problem of categorizing written texts by author gender. Sometimes the decisions of the committee members may reflect individual reliance on an existing high prior (the voters follow the objective prior). On the other hand, the observed decisional capability p of committee members can be relatively low. Empirical evidence regarding the magnitude of p is available in Miller (1996). According to the findings in this study, individual decisional skills of students range between .59 and .65. The above observations regarding the plausibility of high prior and low individual decisional skills suggest that in some real dichotomous choice situations indeed the ratio between the prior and the individual decisional skill is sufficiently large and, in turn, CJT becomes irrelevant.

4 Conclusion

The driving force behind CJT as a pioneering formal justification of democracy is the strength of the people (a sufficiently large voting body) who can attain almost with certainty the true/correct collective choice when applying the simple majority rule. In this context, the prior of a correct collective decision, the precise individual decisional skills and the possibility of strategic voting can be disregarded. This is not the case, however, in the context of committees where the effect of the prior is significant provided that the number of decision makers is small.

In our main results, we have provided the conditions for the PBR to be superior to the SMR, even when the PBR is not optimal, allowing informative as well as strategic voting. These conditions are likely to be satisfied in committees.

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