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Appointed learning for the common good: Optimal committee size and monetary transfers ☆

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ABSTRACT

A population of identical individuals must choose one of two alternatives under uncertainty about the state of the world. Individuals can acquire different levels of costly information and complete contracts are not feasible. For such a setup, we investigate how vote delegation to a committee and suitable monetary transfers for its members can ensure that high or optimal levels of information are (jointly) acquired. We show that for a (stable) committee that uses the majority rule to maximize the probability of choosing the right alternative and then to minimize aggregate information acquisition costs, its size must be small in absolute terms (if full learning is possible) and small relative to population size (if only partial learning is possible). Yet committees must never be made up of one member, so the tyranny of a single decision-maker can be avoided. Our analysis identifies both the potential and some of the limitations of monetary transfers in committee design.

1. Introduction

From a theoretical and empirical viewpoint alike, it has been well understood for a long time that agents have strong incentives to free-ride on others' efforts to find out which alternative is best for the common good (Downs, 1957). Incentives to become informed before voting are low because individuals bear the cost of acquiring the information but their probability of being pivotal is small, particularly in large populations. The problem of there being too little information at the individual level and the aggregate level alike is pervasive both in politics and in corporate governance. It is also salient for numerous panels of appointed experts such as scientific referees, juries, public procurement committees, monetary policy committees, and hiring committees. How should committees of (expert) decision-makers be designed to ensure that a sufficiently high level of information is acquired and later expressed through voting?

An intuitive way of remedying the underinvestment in information in all of the above scenarios is to increase the chances for agents to be pivotal and/or to reduce the private costs associated with information acquisition. In this paper, we explore this double avenue by investigating mechanisms that first appoint a committee of a certain size and second set a suitable

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reward scheme for its members. A *committee* is a (randomly) chosen subset of agents, all of whom are given the exclusive right to vote. A *reward scheme* is a population-wide, budget-balanced vector of monetary transfers.

For the analysis, we use the model of Martinelli (2006). There are two *ex ante* equally likely alternatives and each agent (of the committee) receives an informative signal about the state of the world. The signal's quality can be increased at a cost. Conditional on knowing the state of the world, all agents of the entire population would like to implement the same alternative. Committee members are anonymous and therefore we do not consider the possibility of communication. This is a reasonable assumption for a number of setups, including, but not limited to, groups of citizens who have been randomly chosen from the citizenry, nodes in a blockchain, and scientific reviewers.[1]

We follow the incomplete social contract perspective (see e.g. Aghion and Bolton, 2003) and assume that it is impossible to condition transfers both on the correct state of the world and on the individual votes cast. Rewards cannot depend on the correct state of the world when the latter is revealed much later than payments need to be executed or when it is never revealed independently of the committee decision, since it is precisely the task of an expert committee to find out the state of the world. Transfers that treat members of the majority differently from members of the minority (within the committee) depending on the vote cast may have some drawbacks. First, they may entail a breach of privacy since individual votes must be known to the mechanism. This can be especially undesirable if committee members worry their decisions may impact their careers (see e.g. Gersbach and Hahn, 2008, 2012; Levy, 2007). Vote secrecy applies in many procedures in law.[2] Second, contracting on individual voting behavior may punish the citizen who exerts effort but is unlucky and receives the wrong signal. At the same time, however, it may reward an individual who exerts the same effort level but receives the right signal. Adler and Sanchirico (2006) and Fleurbaey (2010), among others, have put forward several reasons why risk should be evaluated *ex post*.

We further proceed on the assumption that contracts cannot be written that are contingent on the information acquisition costs incurred by the agents. For example, this occurs when such costs are private information, in which case every individual has incentives to claim costs that are higher than those actually incurred.

To channel the agents' incentives to acquire information, we consider the following class of reward schemes: Each member of the committee receives a (positive or negative) transfer that depends on the vote tally difference between the two alternatives obtained after all committee members have voted.[3] This means that we focus on pivotal events, as e.g. in Persico (2004) and Dal Bo (2007), with the difference that our mechanisms cannot use individual votes and rely only on aggregate information about the vote tally. The particular structure of the reward scheme to be chosen depends on whether full learning is feasible or not. In either case, we require the rewards to be uniformly financed by *all* members of the population to ensure that, likewise committee members, all citizens who are not committee members are treated equally.

We show that an adequate reward scheme guarantees that the right alternative is implemented with probability one (if full learning is feasible) or that such probability converges to one with population size (if full learning is unfeasible). To achieve these outcomes at the smallest aggregate information acquisition costs, committees must be small, whether in absolute terms (if full learning is possible) or in relative terms (if full learning is impossible). Roughly speaking, monetary subsidies improve decisions regardless of committee size and enable small committees to yield informed decisions. Importantly, committee size can never be smaller than three, so the possibility that a single citizen dictates policy is avoided, which can be undesirable for a variety of reasons. Our insights carry over to more general setups than our baseline model including asymmetric priors, asymmetric preferences, and private values.[4]

The properties of our family of mechanisms are maintained under the restriction that all citizens—and not just committee members—must keep their right to vote. Giving the right to vote to all citizens of the population is a natural requirement for decisions in a democracy. To show this result, we add a second voting stage to the mechanisms considered, which then corresponds to (a modified version of) Assessment Voting (Gersbach et al., 2021). This is a two-round mechanism that splits the population into two groups that vote sequentially, with all the individuals in the same group voting simultaneously; the first voting group can be thought of as the committee (or *Assessment Group, AG*). All individuals cast one vote, members of the second voting round know the outcome of the first voting round before they vote, and the alternative that receives more votes in the two voting rounds combined is implemented. To be consistent with our framework, we allow all citizens to acquire costly information about the state of the world, no matter which round they vote in. Under AV, we show that only the members of the AG acquire information, so they endogenously become the only experts of the society. The remaining

1 We also assume informative voting, i.e., individuals do not strategize in the use of the information they get (regardless of quality), but simply translate it into a vote. For most of our analysis, this can be done without loss of generality. From Austen-Smith and Banks (1996), we know that, in the absence of transfers, informative voting is rational when the prior is symmetric and the voting rule is simple majority.

2 For example, constitutional courts of countries such as Austria, Belgium, France, or Italy ban the possibility for individual votes to be made public; only the verdict of the court as a whole is public. See https://www.venice.coe.int/webforms/documents/default.aspx?pdffile=CDL-AD(2018)030-e, retrieved on 12 February 2022.

3 Financing is guaranteed when taxation can be enforced, in which case we do not need to be concerned with participation incentive constraints (i.e., with individual rationality). Even if such concerns matter, we show that provided there are enough citizens, at the *interim* stage individuals who are not committee members will prefer to take part in the mechanism than to exit. Committee members, for their part, are content with being part of the committee, so that committees are stable.

4 We also discuss how to choose one particular mechanism from our family of mechanisms, depending on other factors such as robustness against errors and the possibility for committee members not to receive transfers at all or to even have to pay fines with some probability.

citizens do not acquire any information by themselves and simply validate the committee's choice with their vote in the second voting round.

The paper is organized as follows: In Section 2 we discuss the papers that are most relevant for our model. In Section 3 we introduce our model and set up notation. In Section 4 we analyze our family of reward schemes. In Section 5 we consider the case where citizens cannot be deprived of their right to vote. In Section 6 we discuss real-world applications of our family of mechanisms. In Section 7 we investigate some extensions of our baseline setup. Section 8 concludes. The proofs of the main body of the paper are in the appendix.

2. Relation to the literature

Our paper is related to several strands of the literature. First, the formal literature on the Condorcet jury theorem (see e.g. Austen-Smith and Banks, 1996; Castanheira, 2003; Feddersen and Pesendorfer, 1996; Gratton, 2014; Krishna and Morgan, 2012; Ladha, 1992; Persico, 2004; Razin, 2003; Triossi, 2013; Young, 1995) investigates whether *large* elections (or committees) can aggregate dispersed information. When the answer is positive, a strong rationale is provided for working together (e.g. as in democracy). We contribute to this literature by showing how monetary transfers and vote delegation to a *small* committee can be used jointly to overcome low levels of information acquisition in the population at large arising when the accuracy of information is chosen by each individual.

The possibility that with endogenous information vote delegation to a small committee could be better than one-round universal suffrage was already pointed out by Martinelli (2006). However, our insights are broader because besides vote delegation to a committee we consider monetary transfers to the committee members made from the rest of the population. Doing so suffices to yield informed decisions that are expressed through voting for general information acquisition cost functions and population sizes (not just large electorates). In particular, our asymptotic results guaranteeing aggregate learning but individual ignorance for large populations apply more broadly than those in Martinelli (2006). Moreover, our approach yields stable committees and can be extended to give voting right to all citizens (not just committee members). The principle of one-citizen, one-vote is paramount for democracy.

If all citizens have voting power but committee members vote first as in Assessment Voting (Gersbach et al., 2021), committee members become endogenously the only experts in society. Our mechanisms are thus first characterized by the feature that voting power is *fully* delegated to a committee, whether *de jure* or *de facto*. At least since Gilligan and Krehbiel (1987), it is well known that the parent body (in this case, the rest of the population) should have limited rights to amend the decision taken by a committee. This is in line with our insights.

The second main feature of our family of mechanisms is that they use monetary transfers.[5] Winter (2004) argues that even if all agents are *ex ante* equal, monetary transfers, in the form of asymmetric reward schemes, can prompt agents to exert socially efficient effort levels (see also Bernstein and Winter, 2012). Our paper shares this insight in the case of voting: Giving rewards to members of the committee only may be desirable for the common good.[6]

Acquiring costly information that benefits everybody and can be used later for voting is a public good. Hence the positive externalities associated with acquiring information may lead to an underprovision of information. For general public goods, it is known that introducing monetary transfers from some agents to others can introduce negative externalities that compensate the positive externalities set out above (Morgan, 2000). For committee design, Persico (2004) analyzes how (sufficiently large) side-payments can be used to ensure full information acquisition in committees by conditioning rewards on pivotal events (see also Dal Bo, 2007, for a similar mechanism in a setup with private values). While our mechanisms also build on pivotal events, our approach differs insofar as the reward schemes we consider treat every member of the voting body equally *ex post*, since they do not use individual votes.[7]

Some papers have examined optimal committee size by analyzing how voting rules should be designed not only to aggregate dispersed information efficiently but also to induce agents to acquire sufficient information (see Gerling et al., 2005, for a survey on committee design). By letting the vote threshold to upset a status quo vary, Persico (2004) also shows that both the threshold and the committee size relative to the total population should be determined by the information level acquired in equilibrium, and thus be generically above one half, but typically below one. While Persico (2004) considers the voting threshold, we stick to the majority rule and introduce transfer schemes, which produces quite different results.

Finally, our paper is also related to a strand of the mechanism design literature that studies optimal information acquisition mechanisms for committees. In Gerardi and Yariv (2008) communication is possible, and the mechanism designer who participates in the decision chooses both the optimal committee size and how individual decisions translate into the final outcome. Gershkov and Szentes (2009) characterize the optimal stopping rule in a sequential mechanism in which a

[5] If small committees are exposed to external influence, outside payments to sway voters may be directed at committee members. This has been thoroughly studied both theoretically and empirically for lobbying groups trying to buy the vote of legislators (see e.g. Austen-Smith and Wright, 1994; Felgenhauer and Grüner, 2008; Wright, 1990) or of central bank committee members (Gersbach and Hahn, 2008). According to Name-Correa and Yildirim (2018), large committees are better than small ones at avoiding capture from an outsider.

[6] More recently, Azrieli (2021) has examined a setup similar to ours, but he focuses on individual contracts instead of voting by the majority rule.

[7] These reward schemes also feature minimal monetary transfers ensuring high levels of information acquisition for stable committees. This is important for practical implementation, as high monetary transfers can crowd out the direct price effect provided by monetary transfers (see e.g. Gneezy et al., 2011; Meier, 2007).

randomly selected voter is asked to acquire some information in each round.[8] Koriyama and Szentes (2009) study the minimum size of committees guaranteeing *ex ante* efficiency. We differ from these papers insofar that we allow side payments and consider different (continuous) levels of information acquisition. This leads to results about the optimal size that are not in accord with the above papers, as we suggest a lower committee size.

3. Model

Our model builds on Martinelli (2006). There is a population of $2n+1$ individuals who must choose between two alternatives, say A and B. One alternative is the "right" one, i.e., it yields higher utility for all individuals than the other. For simplicity, we normalize the utility obtained from the right alternative to one and the utility obtained from the wrong alternative to zero. However, the right alternative is unknown, as it depends on the (unknown) state of the world. If the state of the world w is A (B), then A (B) is the right alternative. We assume that *ex ante*, the probabilities that either alternative is right are equal to $1/2$. Individuals can obtain a signal about the likelihood of the right alternative, i.e., a signal about the state of the world, yet at some cost. Specifically, there is an *(information acquisition) cost function*

$$c : \left[0, \frac{1}{2}\right] \to \mathbb{R}_+ \cup \{\infty\},$$

where $c(x)$ is the cost in utility units for any individual i of receiving a signal $s_i \in \{A, B\}$ about the state of the world of quality $1/2 + x$ ($x \in [0, \frac{1}{2}]$). This means that for $y \in \{A, B\}$,

$$Prob\big[s_i = y | w = y\big] = \frac{1}{2} + x.$$

Signals are stochastically independent across individuals and $c(x)$ is strictly increasing (and convex, see below). Note that $c(1/2)$ can be infinite, in which case an individual cannot inform himself/herself with certainty about the state of the world.

There is also a committee, which is a subset of $2m+1$ individuals chosen (randomly) from the general population. This means that $m \le n$. Each member i of the committee can decide about his/her own level of information, which we denote by x_i. Once committee members have received their signals, all of them vote simultaneously for one of the alternatives. The alternative that receives at least $m+1$ votes is implemented. We also assume that no abstention occurs. While this is a very strong assumption to impose on the entire population if n is large, it is less demanding for low values of m.[9] Without abstention, the alternative with the largest number of votes is implemented.

Finally, there is a monetary transfer scheme (to be specified later) according to which total payoffs are realized. A *transfer scheme* is a vector $(v_i)_{i=1}^{2n+1} \in \mathbb{R}^{2n+1}$ specifying a payoff for all members of the population, with the property that it is budget balanced, i.e., $\sum_{i=1}^{2n+1} v_i = 0$. Individuals have linear utility in money. This means that when alternative y is implemented and the right alternative is z, the total utility that individual i derives is

$$u_i(z, y, x_i, v_i) := \mathbb{1}_z(y) - c(x_i) + v_i,$$

where $\mathbb{1}_z(y) = 1$ if $z = y$ and $\mathbb{1}_z(y) = 0$ otherwise.

To sum up, we analyze a mechanism that specifies the following sequence of events:

1. The committee is formed.
2. Committee members decide how much information they want to acquire.
3. Committee members receive a signal and cast a vote.
4. The state of the world is realized.
5. A transfer scheme is applied and total payoffs are realized.

We assume that individuals always vote in favor of the alternative that is *interim* most likely, given their signal. If an agent exerts some effort to acquire information, the signal is informative and voting in favor of the other alternative is weakly dominated. If both alternatives are equally likely (i.e., the only information the agents have is the prior), individuals vote according to their signal. This rules out implausible equilibria, with or without transfer schemes, such as the one where no agent procures information and all agents vote for a given alternative. In our setup with monetary transfers and anonymous voting, the latter assumption captures the fact that collusion is difficult.

Following all the above, the (static) game we consider is one in which the player set is composed of all committee members and each player's strategy set is the interval $[0, 1/2]$. We denote this game by $\mathcal{G}^m$, as the committee is made up of $2m+1$ members. For the analysis, we focus on *symmetric* Nash equilibria, i.e., we assume that all players choose the same information level x, with $x \in [0, 1/2]$. This is reasonable in our setup in which all agents are *ex ante* equal. We stress

[8] A general multiparty computation setting is analyzed in Smorodinsky and Tennenholtz (2006).

[9] Abstention in a costly information acquisition setup is analyzed in McMurray (2013) and Oliveros (2013).

that if we take the description of our game at face value, a citizen chooses the level of information s/he wants to acquire but does *not* choose the alternative s/he votes for. This follows from the assumption made above that after each agent i has received a (possibly uninformative) signal, s/he simply follows the recommendation given by the signal.[10]

Finally, we make some assumptions on the cost function $c(x)$ beyond the fact that it is strictly increasing in $[0, 1/2)$. First, $c(x)$ is twice continuously differentiable in the interval $[0, 1/2)$. This assumption is of technical nature and simply facilitates the analysis. Second, as long as $c(x)$ is finite, $c(x)$ is strictly convex, i.e., $c'(x)$ is strictly increasing. This rules out a multiplicity of symmetric equilibria without reward schemes. Third, $c(0) = 0$, so that acquiring zero information is costless. Fourth, $c'(0) = 0$. This last assumption guarantees the existence of equilibria with positive information acquisition.[11]

4. Threshold reward schemes

As mentioned in the Introduction, we assume throughout that the costs to acquire information are private. Alternatively, accrued information acquisition costs may be observable but not contractible, as extensively discussed in the incomplete social contracts literature. If voting takes place privately, as is customary in democratic societies, then the only information that is publicly available is the voting tally, i.e., the number of votes in favor of alternatives A and B.

We shall show that adequate contracting on the vote tally suffices to prompt the committee members to either inform themselves fully or at least to ensure that the probability of selecting the correct alternative converges to one. In such cases, the transfer scheme can act as a device coordinating committee members to acquire a higher level of information. Contracting on the vote tally guarantees that, in equilibrium, the incentives linked to voting pivotality are either zero or close to zero. The only incentives that matter then are those linked to the side-payments contingent on vote tally, which lead to desirable outcomes.

To elaborate, let k denote the vote tally difference between alternatives A and B. That is, if $k > 0$, alternative A received k more votes from the committee members than alternative B in the voting round. Since there is no abstention and the committee has $2m+1$ members, it must be the case that $k \in \mathcal{D}_m$, where $\mathcal{D}_m := \{2l+1 | l \in \mathbb{Z}, -m-1 \leq l \leq m\}$. For each m, with $m \in \mathbb{N}$, we then consider functions

$$\begin{aligned} t^m : \mathcal{D}_m &\to \mathbb{R} \\ k &\to t^m(k), \end{aligned}$$

with

$$t^m(k) = t^m(-k) \text{ for } k \in \mathcal{D}_m. \tag{1}$$

Any such function determines a (positive or negative) reward to any voting outcome based on the absolute difference in terms of votes between alternatives, and hence no matter which alternative receives most votes.

As argued also in the Introduction, we focus on transfer schemes that, from an *ex post* perspective, treat members of the committee equally and individuals outside the committee also equally. That is, given a vote tally difference $k \in \mathcal{D}_m$, for each $i \in \{1, \ldots, 2n+1\}$, we let

$$v_i = \begin{cases} t^m(k) & \text{if } i \text{ is committee member,} \\ -\frac{2m+1}{2(n-m)} \cdot t^m(k) & \text{if } i \text{ is not committee member.} \end{cases} \tag{2}$$

If $t^m(k) > 0$, rewards to the committee members are financed homogeneously by the rest of the population. If $t^m(k) < 0$, the committee members subsidize the rest of the population. A transfer scheme defined as in (2) is called a *threshold (reward) scheme*, or *TS* for short. The only information a TS uses beyond the vote tally is whether a given individual belongs to the committee or not.

With a TS, by accounting for all possible events, the expected utility of any member i of the committee (for a given size $2m+1$) when s/he chooses information acquisition level $x_i \in [0, 1/2]$ and all the other $2m$ members of the committee choose $x \in [0, 1/2]$, as demanded by our notion of symmetric equilibrium, is

$$\begin{aligned} U_i(x_i|x) = &\binom{2m}{m} \cdot \left(\frac{1}{2}+x\right)^m \left(\frac{1}{2}-x\right)^m \left(\frac{1}{2}+x_i\right) - c(x_i) + \chi \\ &+ \sum_{k=1}^{m} \binom{2m}{m+k} \left(\frac{1}{2}+x\right)^{m+k} \left(\frac{1}{2}-x\right)^{m-k} \left[\left(\frac{1}{2}+x_i\right) \cdot t^m(2k+1) + \left(\frac{1}{2}-x_i\right) \cdot t^m(2k-1)\right] \end{aligned}$$

[10] An exception is Section 7.1.

[11] If $c'(0) > 0$, the mechanisms we propose could be used to increase the pivotality of the committee members to generate positive information acquisition in equilibrium.

$$+\sum_{k=1}^{m}\binom{2m}{m+k}\left(\frac{1}{2}+x\right)^{m-k}\left(\frac{1}{2}-x\right)^{m+k}\left[\left(\frac{1}{2}+x_i\right)\cdot t^m(2k-1)+\left(\frac{1}{2}-x_i\right)\cdot t^m(2k+1)\right]$$
$$+\binom{2m}{m}\left(\frac{1}{2}+x\right)^{m}\left(\frac{1}{2}-x\right)^{m}\cdot t^m(1), \tag{3}$$

where χ is a component of utility that does not depend on x_i. To understand Equation (3), note that the first term on the right-hand side captures individual i's expected utility for casting a vote following his/her signal if s/he incurs cost x_i, conditional on being pivotal. The probability of the latter event when all committee members other than individual i choose information level x is equal to

$$P_x[\text{tie}]=\binom{2m}{m}\cdot\left(\frac{1}{2}+x\right)^{m}\cdot\left(\frac{1}{2}-x\right)^{m}.$$

The second term on the right-hand side of Equation (3) is the cost to acquire information level x_i. Then, the two sums on the right-hand side of Equation (3) capture the expected transfer individual i will receive when casting his/her vote after having acquired a signal of quality $1/2+x_i$, conditional on the votes of the remaining individuals of the committee yielding a given margin in the vote tally. These margins are indexed by k. A vote can increase or decrease the vote margin. The first sum captures the case when there are at least as many votes for the right alternative as there are for the wrong alternative, with the second sum capturing the case when there are at least as many votes for the wrong alternative as there are for the right alternative. Finally note that if $t^m(k)=0$ for all $k\in\mathcal{D}_m$, Equation (3) reduces to the case of standard voting with turnout equal to $2m+1$.[12]

Next recall that we are assuming (1). Therefore, if we denote

$$\phi^m(l)=t^m(2l+1)-t^m(2l-1) \text{ for all } l\in\{0,\dots,m\}$$

it follows that for all $x_i\in(0,1/2)$,

$$U_i'(x_i|x)=\binom{2m}{m}\cdot\left(\frac{1}{4}-x^2\right)^{m}-c'(x_i)$$
$$+\sum_{l=1}^{m}\binom{2m}{m+l}\cdot\phi^m(l)\cdot\left(\frac{1}{4}-x^2\right)^{m-l}\cdot\left[\left(\frac{1}{2}+x\right)^{2l}-\left(\frac{1}{2}-x\right)^{2l}\right]$$

and

$$U_i''(x_i|x)=-c''(x_i)<0.$$

Accordingly, a necessary and sufficient condition for a strategy profile $(x,\dots,x)$, with $x\in(0,1/2)$, to be an equilibrium of game $\mathcal{G}^m$ is

$$c'(x)=\overbrace{\binom{2m}{m}\cdot\left(\frac{1}{4}-x^2\right)^{m}}^{:=A(x)}$$
$$+\underbrace{\sum_{l=1}^{m}\binom{2m}{m+l}\cdot\phi^m(l)\cdot\left(\frac{1}{4}-x^2\right)^{m-l}\cdot\left[\left(\frac{1}{2}+x\right)^{2l}-\left(\frac{1}{2}-x\right)^{2l}\right]}_{:=B(x)}. \tag{4}$$

If $m>0$, two important observations follow readily from the above expression. First, since $c'(0)=0$, if $\phi^m(l)=0$ for all $l\in\{1,\dots,m\}$, then Equation (4) has exactly one solution, say x. The reason is that $c'(\cdot)$ is strictly increasing, $A(\cdot)$ is decreasing, $A(1/2)=0$, and $c'(0)=0$. Hence, $(x,\dots,x)$ is the only symmetric equilibrium of $\mathcal{G}^m$. This captures one-round, simultaneous voting within a committee. If $\phi^m(l)\neq 0$ for some $l\in\{1,\dots,m\}$, by contrast, neither uniqueness nor existence of (interior) symmetric equilibria is guaranteed. Clearly, because $c'(0)=0$ and $A(0)+B(0)>0$, the strategy profile where no committee member acquires information, namely $(0,\dots,0)$, cannot be an equilibrium. If, moreover,

$$A(x)+B(x)>c'(x) \text{ for all } x\in(0,1/2), \tag{5}$$

the only symmetric equilibrium of $\mathcal{G}^m$ is the strategy profile in which all committee agents acquire full information, namely $(1/2,\dots,1/2)$. By contrast, if (5) does not hold, then there is at least one (interior) symmetric equilibrium $(x,\dots,x)$, with $x\in(0,1/2)$. But there may be other equilibria, including $(1/2,\dots,1/2)$.

[12] This is the case analyzed by Martinelli (2006).

The second important observation from (4) is that $\phi^m(0) = t(1) - t(-1) = 0$, so the exact value of $t(1)$ and $t(-1)$ is immaterial for equilibrium. This is because in the event that a citizen breaks a tie, s/he will create a difference of one vote, no matter which alternative s/he votes for. While this is relevant for the utility citizens derive from the alternative implemented, it does not affect the incentives to be informed, conditional on being pivotal. This is reminiscent of the swing voters' curse (Feddersen and Pesendorfer, 1996; Herrera et al., 2019a,b). As we discuss below, the exact value of $t(1) = t(-1)$ *does* matter for the extent of transfers and for participation incentives, i.e., for individual rationality.

For each integer $m \geq 0$, we consider in the following functions such as

$$\phi^m : \{-1, 0, 1, \dots, m\} \to \mathbb{R}$$
$$l \to \phi^m(l),$$

with $\phi^m(0) = 0$. Since $\phi^m(\cdot)$ determines $t^m(\cdot)$ with one degree of freedom, we also adopt the convention that $\phi^m(-1) = t^m(1)$. This guarantees that there is a one-to-one correspondence between $\phi^m(\cdot)$ and $t^m(\cdot)$, and it allows us to write $t^m(2l+1) = \sum_{l'=-1}^{l} \phi^m(l')$ for all $l \in \{0, 1, \dots, m\}$. We stress that $\phi^m(l)$, with $l > 0$, rewards (or punishes) a marginal vote even if it does not break a tie in the election. Such rewards may arise in normal elections if voters care about the victory margin, and they might be significant (Herrera et al., 2019b). In our setup, these rewards are chosen by design.

For the subsequent analysis, we proceed with a general information acquisition cost function $c(x)$ fulfilling our assumptions and distinguish two cases, depending on the value of $c'(1/2)$.

4.1. Full information

First, we consider the case where $c'(1/2) < \infty$. This means that it is theoretically possible to find out with full precision what the right alternative is (at a finite cost). For this case, we start by considering the following reward scheme:

$$\phi^m(l) = \begin{cases} c'(1/2) & \text{if } l = m, \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

The TS defined in (6) only rewards decisions that are reached unanimously within the committee. If unanimity is reached, each of the committee members is given a transfer that amounts to $c'(1/2)$. A unanimous decision can opt for the correct alternative or the incorrect one. Unless all the members of the committee inform themselves perfectly, both options will occur in equilibrium, albeit possibly with different probabilities.

We start by showing the following result:

Proposition 1. *Suppose the TS is defined by (6) for a given integer $m \geq 1$. Then the strategy profile in which all members of the committee acquire complete information, $(1/2, \dots, 1/2)$, is an equilibrium of $\mathcal{G}^m$.*

Proof. See appendix. □

From the proof of Proposition 1, one immediately sees that provided $c'(1/2) < \infty$, a necessary and sufficient condition for $(1/2, \dots, 1/2)$ to be an equilibrium of $\mathcal{G}^m$ is

$$\phi^m(m) \geq c'\left(\frac{1}{2}\right). \tag{7}$$

The intuition for this result is clear. The TS must reward the marginal effort of acquiring another piece of information beyond x sufficiently. This effort is highest when x is (infinitely) close to $1/2$ because $c(x)$ is convex. Assuming that $\phi^m(l) \geq 0$ for $l \in \{-1, 0, \dots, m-1\}$ implies that the transfers that each member who is not part of the committee must pay to the members of the committee to ensure full information acquisition can never be lower than

$$\frac{2m+1}{2(n-m)} \cdot c'\left(\frac{1}{2}\right). \tag{8}$$

In Proposition 1, we have assumed $m \geq 1$, so that the committee consists of at least three members. If $m = 0$, and hence the committee consists of only one member, the reward scheme defined in (6) has no bearing on the unique committee member's calculus for maximizing his/her utility (see Equation (3)), which is accordingly

$$\max_{x \in [0,1/2]} [x - c(x)].$$

The solution to the above problem is generically different from $1/2$. Why is the case with more committee members different? If there are at least three members in the committee, all the incentives for becoming informed due to (voting) pivotality disappear if the strategy profile of Proposition 1 is played. This is because all individuals inform themselves

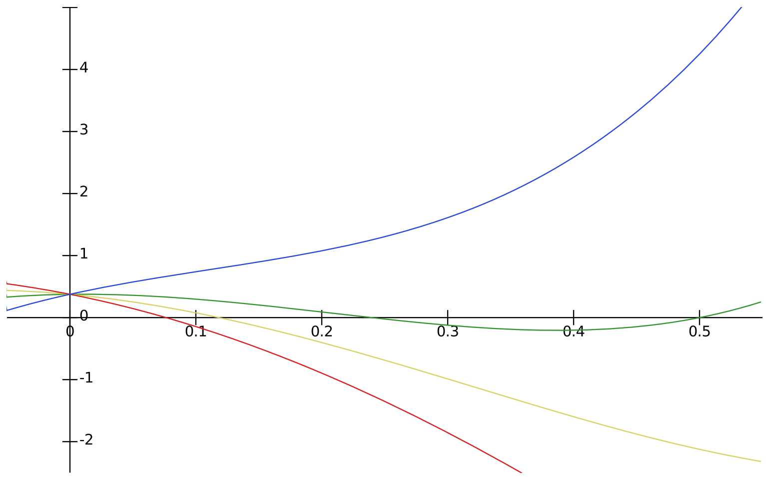

Fig. 1. Function $(A(x) + B(x)) - c'(x)$—see Equation (4)—when $\phi^2(0) = \phi^2(1) = 0$ and the reward for unanimity, $\phi^m(2)$, takes different values. The blue (uppermost) curve corresponds to $\phi^2(2) = 2c'(\frac{1}{2})$, the green (second from the top) curve corresponds to $\phi^2(2) = c'(\frac{1}{2})$ (see Example 1), the yellow (third from the top) curve corresponds to $\phi^2(2) = \frac{1}{2}c'(\frac{1}{2})$, and the red (lowest) curve corresponds to no rewards, i.e., $\phi^2(2) = 0$. An interior equilibrium exists when the curve intersects the x-axis between 0 and 1/2. A full information equilibrium exists when the curve is not negative at $x = 1/2$.

perfectly and vote for the right alternative. As a consequence, no single individual can change the voting outcome (which is determined by the majority rule). The only incentives left for informing oneself are those linked to the TS. If $\phi^m(m) \geq c'(1/2)$, convexity of $c(x)$ guarantees that the strategy profile of Proposition 1 is an equilibrium. In this equilibrium, all members of the committee inform themselves fully, so that the equilibrium is inefficient in that duplicate information is acquired. Conditional on implementing the right alternative with probability one, such (welfare) inefficiency is therefore minimized for $m = 1$.

While Proposition 1 ensures that full information acquisition is an equilibrium, there may be other equilibria with partial information acquisition. This is shown next and warns us that ill-designed transfers may have consequences for outcomes.

Example 1. Consider $c(x) = 3x^3 + 2x^2$ and $m = 2$, and assume that the TS defined by (6) is used. Then game $\mathcal{G}^m$ has two equilibria: one equilibrium in which all citizens choose $x = 0.5$ and another equilibrium in which all citizens choose $x \approx 0.24$. Fig. 1 illustrates this multiplicity of equilibria by plotting function $(A(x) + B(x)) - c'(x)$ when the TS defined by (6) is used, as well as when other rewards for unanimity are considered—see Equation (4).

To deal with uniqueness of (symmetric) equilibria, we consider now the following TS:

$$\phi^m(l) = \begin{cases} \frac{4^{m-1}}{2m} \cdot r_m & \text{if } l = m, \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

In (9), $(r_m)_{m \geq 1}$ is a certain increasing sequence that depends on cost function $c(x)$, is bounded from above, and satisfies that for all $m \geq 1$,[13]

$$\frac{4^{m-1}}{2m} \cdot r_m \geq c'\left(\frac{1}{2}\right). \tag{10}$$

It is important to note that Inequality (10) need not be tight.

We obtain the following result:

Theorem 1. *Suppose the TS is defined by* (9) *for a given integer* $m \geq 1$. *Then the strategy profile in which all members of the committee acquire complete information,* $(1/2, \ldots, 1/2)$, *is the only symmetric equilibrium of* $\mathcal{G}^m$.

Proof. See appendix. □

The above theorem shows that regardless of the size of the committee, one can always find finite rewards for its members that induce *each* of them to acquire full information. Such rewards exclude the possibility that other equilibria exist

[13] The value of r_m is independent of n, provided that $n \geq m$. Hence, sequence $(r_m)_{m=0}^{\infty}$ implicitly assumes that as m grows, so must n. We refer to the proof of Theorem 1 for details about such a sequence.

with suboptimal information acquisition levels. They do so by rewarding unanimity enough so that, given any such sub-optimal information level, all individuals prefer to marginally acquire more information and increase the probability of unanimity being reached, and hence of receiving the reward. While this result is intuitive for arbitrarily large rewards, Theorem 1 achieves more, as it sets an upper bound to the rewards ensuring a unanimous decision with probability one.

Using the fact that $(r_m)_{m\geq 1}$ is bounded from above, we let r denote the infimum of any such bound. Then, individual rewards for committee members are bounded (from above) by

$$\frac{4^{m-1}}{2m}\cdot r.$$

This means that the amount each individual who is *not* a member of the committee needs to contribute can be bounded (from above) by

$$\frac{4^{m-1}\cdot r}{(n-m)}.$$

Hence, as long as m can be chosen such that $m=\Theta(\ln n)$, individual contributions to the rewards for committee members do not grow unbounded. This means that if full information acquisition is possible, a *sufficient* condition for committees to implement the correct alternative with probability one through a feasible reward scheme is that the size of the committee grows logarithmically with the total population. This is important for real-world implementation of the mechanism that uses the TS defined by (9), and more generally for the use of monetary transfers in committee design. On the other hand, it is straightforward to see that as far as the mechanism using the TS defined by (9) is concerned, it is always preferable from a welfare perspective to choose $m=1$ over any $m>1$. The reason is that both options set committees that implement the correct alternative with probability one, but $m=1$ involves the lowest aggregate information costs.

In the following, we show that it is possible to compensate the committee members for the costs associated with acquiring full information and, at the same time, approximate the bound given in (7). To this end, consider the following reward scheme:

$$\phi^m(l)=\begin{cases} c'\left(\frac{1}{2}\right) & \text{if } l=m,\\ t_m>0 & \text{if } l=l',\\ -t_m-z<0 & \text{if } l=-1,\\ 0 & \text{otherwise,}\end{cases} \tag{11}$$

where $l'\in\{1,\dots,m-1\}$, and $t_m>0$ and $z\in\mathbb{R}$ are parameters that need to be determined. Implementing the mechanism that uses the TS defined by (11) requires $m>2$, i.e., the committee must consist of at least seven members.

We obtain the following result:

Proposition 2. *Suppose the TS is defined by* (11) *for a given integer $m>2$. Then the strategy profile in which all members of the committee acquire complete information,* $(1/2,\dots,1/2)$*, is the only symmetric equilibrium of $\mathcal{G}^m$, provided that parameter t_m is sufficiently large.*

Proof. See appendix. □

The above result guarantees that, under uniqueness of equilibria, the bound defined by (7) is attainable. That is, the marginal reward for being pivotal to attain unanimity is $c'(1/2)$. The TS defined by (11) works by setting large punishments if slim majorities are reached. While these majorities will not occur on the equilibrium path (of the unique equilibrium), such punishments are crucial off the equilibrium path to ensure that no other equilibria exist beyond the full information acquisition equilibrium. As captured by Theorem 1 and Proposition 2, there is therefore a trade-off between lowering the reward for unanimity and increasing the punishment if the outcome deviates from unanimity.

It remains an open question whether the result of Proposition 2, together with the property that the bound given in (7) is binding, can be obtained without any (off-equilibrium) fines (i.e., without the possibility that committee members make monetary transfers to the rest of the population). Nevertheless, below we discuss the relevance of the off-equilibrium fines associated with the TS defined by (11) from the perspective of a social planner with preferences equal to those of the citizens.

Suppose now, for instance, that $l'=1$ for the above TS. Then a majority of one vote for either alternative in the voting tally is punished by $-t_m-z$, a majority of at least three votes that is short of unanimity is punished by $-z$, and unanimity is rewarded by $c'(1/2)-z$. Since z only enters in $\phi^m(-1)$, the exact value of z does not matter for equilibrium. This implies that the transfers committee members expect to receive, namely $c'(1/2)-z$, can be set to any value, in particular to zero if $z=c'(1/2)$. In such a case, there will be no transfers in equilibrium. As we discuss below, the (expected) extent of the transfers that committee members receive in equilibrium does matter for committee stability, since it affects individual rationality constraints, thereby setting a bound on the values of z that should be considered.[14]

Choosing very large values of z will also matter substantially if committee members were to make unexpected mistakes, since large punishments would then have to be paid by committee members.[15] However, a social planner may want to avoid such an outcome at all costs, since it may not be very practical. Should such (real-world) concerns need to be taken into account, the social planner could set $z = 0$ and take sufficiently large values of m. It then follows that as m, and hence n, increases asymptotically, the probability that *any* committee member would have to pay a positive transfer would go to zero even if these individuals made (small) mistakes. For concreteness, suppose that each committee member makes an unexpected mistake with some (committee size-independent) probability $\delta \approx 0$. Then, the probability that a committee member will have to pay a fee if the TS defined by (11) is in place is

$$\pi_m := \binom{2m+1}{m+1} \cdot (1-\delta)^{m+1}\delta^m + \binom{2m}{m} \cdot (1-\delta)^m \delta^{m+1} \approx \binom{2m}{m} \cdot \delta^{m+1}.$$

One can easily verify that π_m goes to zero very rapidly with m. This means that m need not be very large to ensure arbitrarily low values of π_m. This is important insofar as for sufficiently large values of n, committee size could still be small (in relative terms). By the same logic, the rewards to committee members would be paid with very low probability, since unanimity would be very unlikely. Yet, the right probability would be implemented with probability close to one.[16] The TS defined in Section 4.2 differs from the one defined by (11) in that committee members never pay transfers on and off the equilibrium path. Should the social planner want to avoid the feature that transfers may be paid, even if with a tiny probability, s/he could therefore use the former TS instead of the latter. Moreover, the TS defined in Section 4.2 pays the same positive transfers to committee members not only for unanimity but for most majority vote margins, and thus such transfers may be seen as less fragile than those used by the TS defined by (11).

Proposition 2 bears some resemblance to a finding by Persico (2004), but it differs in some important respects.[17] Both results show that large rewards or punishments can ensure full information. In such cases, incentives related to pivotality vanish (in the limit), and individuals focus entirely on avoiding the punishments. While in Persico (2004) the large rewards must be given in equilibrium, we show that large punishments are only needed *off* equilibrium. More importantly, although we both build on pivotal events, our class of mechanisms does not rely on individual votes. Hence, it rewards or punishes all committee members equally. The appeal of this property has been discussed in the Introduction. Proposition 2 is *also* a complement of Persico (2004) insofar as it determines a tight bound for the transfers to be given to the committee members, and it does so for arbitrary information acquisition functions.

As mentioned above, the (expected) extent of transfers plays an important role for the incentives of the citizens to participate in the mechanism. To see this, assume that when some TS in place, each of the committee members is given a positive transfer conditional on unanimity, say b_m, satisfying

$$b_m \geq c'\left(\frac{1}{2}\right). \tag{12}$$

Condition (12) is satisfied by all the TS analyzed in this section. (For the TS defined by (11) it suffices to consider $z = 0$.) Because of (2), this means that every other individual in the society must incur a disutility equal to $-\frac{(2m+1)\cdot b_m}{2(n-m)}$. If full information is the only equilibrium (and hence the right alternative will be chosen with probability one), every individual of the population expects utility 1 from the alternative being implemented.

For our analysis of committee stability, we proceed on the assumptions that *(i)* not participating in the mechanism requires abandoning the population altogether, which yields some utility $u < 1$, and *(ii)* refusing to be a committee member but not a member of the population simply induces the selection of another citizen for the committee (if the latter has an incentive to do so). Part *(i)* prevents individuals from free-riding completely on the alternative eventually implemented. In democratic societies taxation can be enforced by law, so such participation constraints can be ignored. In other situations—see e.g. Section 6—imposing part *(i)* is realistic. Part *(ii)* ensures that not participating in the mechanism does not affect the probability that the right alternative is implemented.[18] It thus provides the highest incentives (if any) for a citizen who is a member of the committee to exit the committee (but not the population) rather than to stay, all else being equal.

Accordingly, for those who are not committee members to be willing to participate in the mechanism and not to leave the population altogether, the *interim* participation condition (i.e., the participation condition after the committee has been constituted but before the vote takes place and the state of the world is realized) is

[14] Recall that individuals have linear utility in money.

[15] Similar problems would arise if there was an unknown share of partisan voters or some voters lacked sophistication.

[16] With expected mistakes, one would need to modify the TS defined by (11) to ensure that not only large punishments are avoided with probability close to one, but also that rewards are received by committee members with very high probability.

[17] See Section 7 in Persico (2004).

[18] Part *(ii)* can be dispensed with if m is sufficiently large, as lowering the size of the committee will have a small impact on the probability that the right alternative is implemented.

$$u < 1 - \frac{2m+1}{2(n-m)} \cdot b_m.$$

The above individual rationality condition is satisfied if n is large enough for a given $m \geq 1$. As for the committee members, they neither want to exit the committee nor the population from an *interim* perspective. From Inequality (12), it follows that

$$1 - c\left(\frac{1}{2}\right) + b_m \geq 1 + c\left(\frac{1}{2}\right) > 1 > u.$$

The first inequality is due to the fact that $c'(x)$ is increasing and $c(0) = 0$, so

$$\frac{1}{2} \cdot c'\left(\frac{1}{2}\right) = c(0) + c'\left(\frac{1}{2}\right) \cdot \frac{1}{2} > c\left(\frac{1}{2}\right).$$

Finally, from an *ex ante* perspective (i.e., before the committee is formed), it is clear that all individuals will want to participate in the mechanism if the population is large enough.

4.2. Partial information

Next we consider that $c'(1/2) = \infty$, in which case one single individual cannot inform himself or herself perfectly about the state of the world. This implies, in turn, that no finite population can learn about the state of the world with probability one. Only asymptotic results are possible. For this case, we assume that

$$c''(0) < \infty. \tag{13}$$

Then, for any $\varepsilon > 0$, we consider the following reward scheme:

$$\phi^m(l) = \begin{cases} m^{\frac{1}{2}+\epsilon} \cdot g_n(m) & \text{if } l = 1, \\ 0 & \text{otherwise,} \end{cases} \tag{14}$$

where for all $m, n \in \mathbb{N}$, with $m \leq n$, we select functions $g_n(m)$ with the properties

$$0 \leq g_n(m) \leq g_n(m-1) < \infty, \tag{15}$$

and

$$\lim_{m,n \to \infty} g_n(m) = c''(0) < \infty. \tag{16}$$

The TS defined by (14) rewards any vote difference larger than one equally, so it is very different from the TS analyzed in Section 4.1 which target unanimity. Provided that Condition (13) holds, our analysis remains valid also for full learning, i.e., for $c'(1/2) < \infty$. In such a case, in order to choose among the different TS of both this section and the previous section, one should weigh the probability of choosing the right alternative, expected information acquisition costs, committee size, and population size against features such as robustness against errors and the possibility for committee members not to receive transfers at all or to even have to pay fines with some probability. We refer to the proof of Proposition 2 (see appendix) for more details about functions $g_n(m)$. Here it suffices to note that thanks to Condition (13), the TS defined by (14) is well defined. If Condition (13) did not hold, then (15) and (16) would require committee members to receive an infinite amount of money.

The next result shows that, as m (and hence n) goes to infinity, the mechanism that uses the TS defined above chooses the right alternative with probability one asymptotically. Because we examine a limit result, we assume that for any given $m \in \mathbb{N}$ such that the committee consists of $2m + 1$ members, total population amounts to $2f(m) + 1$, with $f(m) \geq m$. Then statements about convergence when m grows require n to grow as described by $f(m)$. In particular, we can assume that

$$\lim_{m \to \infty} \frac{m}{f(m)} \cdot m^{\frac{1}{2}+\varepsilon} = \lim_{m \to \infty} \frac{m^{\frac{1}{2}+\varepsilon}}{\frac{2f(m)+1}{2m+1}} = \lambda, \tag{17}$$

with $0 \leq \lambda < 1$. This implies that relative committee size converges to zero as total population grows. Assuming (17), we obtain

$$0 \leq \lim_{m \to \infty} \frac{(2m+1) \cdot \phi^m(1)}{2(f(m) - m)} = \lambda \cdot c''(0) < c''(0),$$

where the last inequality holds due to Condition (13). The latter condition specifies the (limit) amount that individuals who are not members of the committee need to pay in the case of very large populations when the reward scheme defined by (14) is used. Due to Condition (13), such a bound exists and is finite.

Let us now use Q_m to denote the probability that the right alternative is implemented if the committee is made up of $2m+1$ individuals and each of them incurs cost x_m^*. One can easily verify that

$$Q_m = Q_m(x_m^*) := \sum_{i=m+1}^{2m+1} \binom{2m+1}{i} \cdot \left(\frac{1}{2}+x_m^*\right)^i \cdot \left(\frac{1}{2}-x_m^*\right)^{2m+1-i}. \tag{18}$$

We can now present our next result, which investigates the asymptotic behavior of Q_m when the TS defined by (14) is used.

Theorem 2. *Assume that Condition (13) holds and that the TS is defined by (14) for any integer $m \geq 1$. Then, for any sequence $(x_m(f(m)))_{m\geq 1}$ where $(x_m(f(m)), \ldots, x_m(f(m)))$ is a symmetric equilibrium of $\mathcal{G}^m$,*

$$\lim_{m\to\infty} Q_m = 1.$$

Proof. See appendix. $\square$

As it can be seen in the proof of the above result, the information level acquired in any symmetric equilibrium, x_m^* for a given committee size m, tends to zero as m tends to infinity. This is intuitive since, as m goes to infinity, individual rewards do not grow unboundedly and pivotality (both for the voting outcome and for the transfers) goes to zero. However, the individual information levels remain large enough to ensure that the probability of the right alternative being chosen by a majority of the committee converges to one. This result is reminiscent of the positive asymptotic results in Martinelli (2006), in which individual ignorance is not at odds with aggregate learning. But in our case introducing monetary transfers enables such (positive) result to hold much more generally for different cost functions.

Theorem 2 also holds no matter the size of the committee compared to the total population. Moreover, if Condition (17) holds for $\lambda = 0$, individual transfers made by non-committee members converge to zero for arbitrarily large populations. This means that there is no other mechanism of the type considered in this section that is more (asymptotically) efficient for large populations than the one that uses the TS defined by (14), since the latter mechanism chooses the right alternative with any desirably high probability at an average information cost that goes to zero. Also note that since a margin of one vote will occur with arbitrarily low probability, the same transfer $m^{\frac{1}{2}+\epsilon} \cdot g_n(m)$ will be made to the committee members with arbitrarily high probability even if committee members make small (unexpected) mistakes. This contrasts with the different TS examined in Section 4.1.

Finally, individual rationality constraints can be satisfied, so committees under the mechanism that uses the TS defined by (14) are stable. Indeed, for those citizens who are not committee members, the *interim* participation condition is

$$u < \lim_{m\to\infty} Q_m - \frac{(2m+1)\cdot\phi^m(1)}{2(f(m)-m)} = 1 - \lambda \cdot c''(0).$$

The above inequality holds if a sufficiently small λ is assumed. As for the committee members, the *interim* participation condition is

$$\lim_{m\to\infty} Q_m - c(x_m) + m^{\frac{1}{2}+\varepsilon} g_n(m) \geq 1 - c(0) = 1 > u.$$

As in Section 4.1, from an *ex ante* perspective all individuals will want to participate in the mechanism if the population is large enough.

5. Assessment voting

Suppose now that to implement an alternative, every agent must be given the right to vote on whether or not this alternative will be implemented. Departing from the setup in the previous sections, *one* possible way to do so is for individuals who are not part of the committee to (simultaneously) vote in a voting round that takes place after the result of the first voting round by committee members has been made public (and transfers have been made). The votes collected by each alternative in both rounds are added, and the alternative with more votes is implemented (recall that there cannot be ties if all citizens vote). This mechanism is called *Assessment Voting* (in short AV, Gersbach et al., 2021). An additional assumption that can be made is that committee members are chosen randomly from the population. AV is particularly appealing in our setup when standard democratic desiderata—such as one-person, one-vote—need to be met.

We claim that if a strategy profile $(x, \ldots, x)$, with $x \in (0, 1/2]$, is an equilibrium of the *static* game where only committee members vote, the strategy profile in which *(i)* all members of the committee choose information acquisition level x and *(ii)* all other citizens acquire zero information and vote for the alternative that collected more votes in the first round is a sequential equilibrium of the *dynamic* game underlying AV, provided the following two properties. First, the total population is sufficiently large. Second, individuals with the same information in the second round vote in favor of the same alternative.

Then we find that committee members become the only experts in the population. Non-committee members anticipate that they will not be pivotal and do not acquire any information.[19]

We need to show that the above claim is correct. Assuming behavior of the second-round citizens as described by property *(ii)*, the problem faced by the first-round citizens—the (expert) committee members—is the same as in the baseline setup with only one round. This is because the right alternative is implemented if and only if it obtains most votes in the first voting round. As for the second round, note that the individuals with the right to vote in this round must use Bayes' rule to find the posterior probability that alternative A is the right one. This posterior belief, denoted by q, depends on x and m (the committee size) as well as on the difference in votes between the two alternatives k (with $k \in \mathcal{D}_m$), and it satisfies

$$q = q(x, m, k) \begin{cases} > \frac{1}{2} & \text{if } k > 0, \\ < \frac{1}{2} & \text{if } k < 0. \end{cases}.$$

The above inequalities hold because the initial prior is 1/2, committee size is odd, and because according to property *(i)* committee members vote after they have acquired some information $x > 0$. The latter property holds for all the mechanisms examined in the paper. We stress that $k > 0$ ($k < 0$) means that alternative A received more (less) votes than alternative B in the first voting round.

Then we have the following result, which focuses on the second round of AV after the first round took place with some TS of those analyzed in the previous section:

Theorem 3. *Given x, m, q, and k, in any Nash equilibrium of the (static) game underlying the second round of AV, it must be the case that if n is sufficiently large, then all citizens with a right to vote in the second round (i) gather zero information and (ii) vote for the alternative that received more votes in the first (committee) voting round.*

Proof. See appendix. □

Accordingly, our insights from the previous sections carry over to AV, since committee members anticipate that an alternative will be eventually chosen if and only if it is chosen by the committee. Theorem 3 applies for all TS examined in the paper and therefore adds to the properties of AV (Gersbach et al., 2021) as a potential decision-making procedure.

6. Real-world applications

One close real-world application of our family of mechanisms is a (blockchain) platform providing *decentralized justice* called kleros.io.[20] This is an Ethereum organization working as a decentralized third party that arbitrates disputes between two parties who must commit to the outcome. It operates by selecting a random set of *anonymous* jurors from a large pool of candidates. Once they are chosen, jurors are given all the material necessary to understand the dispute and must submit a vote after three days (they cannot abstain and can only vote in favor of one of the two parties in the dispute). Jurors are then given a monetary reward if they vote with the majority, in line with Persico (2004). Such compensation schemes incentivize jurors to acquire information by exerting some effort in evaluating the material they receive. While the used compensation schemes differ from our family of mechanisms insofar as the former treat committee members unequally *ex post*, our mechanisms could have some advantages if they were implemented on the platform. Although juror anonymity makes it already difficult for the jurors to collude, from the individual rewards one can in principle infer the vote, which could lead to a breach of anonymity (and of privacy). The latter features could, hence, be better protected if the platform used transfer schemes like the ones we consider, which give equal rewards based on the vote margins and make it impossible to learn the vote from the reward received. We note that kleros.io praises the importance of juror anonymity and privacy.[21] We stress that our results show that imposing such privacy features does not come at the price of lower accuracy in outcomes.

From a broader perspective, vote margins are associated with monetary and non-monetary rewards. In many countries, e.g. in Germany, parties receive funding from the state according to the vote-share they obtained in the elections.[22] Vote margins are easy to compute and to use, and they have the potential to channel the right incentives. If we focus on non-monetary rewards, then vote-share differences are essential in jury decisions. If a jury's verdict entails time in prison or even a death penalty, typically unanimity is required since there should be no doubt left about such an irrevocable decision. One can then argue that the monetary reward for consensus in that particular case is irrelevant. Sharing the responsibility

[19] The payments made in the first voting round are sunk when the second voting round starts. We rule out the possibility of side-payments in the second voting round in AV.

[20] See https://kleros.io/whitepaper.pdf, retrieved 10 February 2022.

[21] The importance of anonymity as a tool to avoid the capture of the committee by an outsider is stressed in Name-Correa and Yildirim (2018).

[22] For Germany, see https://www.bmi.bund.de/DE/themen/verfassung/parteienrecht/parteienfinanzierung/parteienfinanzierung.html, retrieved 16 February 2022.

for the decision with the other members of the jury and having eliminated all possible doubts certainly alleviates the moral burden of the verdict for each jury member. Introducing monetary rewards as we do when the moral imperative is weaker could be used to restore the right incentives to acquire costly information in such situations.

Blockchains are potential applications for our mechanisms with a randomly selected committee (Atzori, 2015; Beck et al., 2018; Paech, 2017). Achieving consensus on blockchains and obtaining rewards for validation of transactions is directly connected to vote-share differences. For the validation of transactions in consensus protocols, a majority of validators often comprises at least two thirds of their votes. If this threshold is not attained, no rewards are distributed as either the transaction is not validated or the blockchain is disrupted, see Dinsdale-Young et al. (2020) and David et al. (2018). Furthermore, governance has become a central issue for any blockchain beyond consensus, as the evolution of the blockchain itself requires repeated collective decisions. Our paper suggests a family of mechanisms that could be used to improve the governance of blockchains without very large overhead costs.

The mechanisms we propose—vote delegation to a committee, coupled with a transfer scheme—could also be used in the case of large populations instead of population-wide referenda (e.g. as an *online voting* procedure), provided that committee members were chosen at random from the entire population. There is a growing strand of research attempting to find (new) mechanisms for collective democratic decisions that can correct some inefficiencies of the decision-making procedures currently in place (see e.g. Gersbach et al., 2021; Lalley and Weyl, 2018). As far as side-payments are concerned, central (governmental) authorities have the power to execute such payments. Alternatively, payments could be implemented via *Smart Contracts* in the absence of such an authority since, as we have argued, individual rationality constraints are addressed by our mechanisms. As to the composition of the committee, Micali and Cheng (2017) argue that a verifiable random function can be implemented via blockchain, which could achieve fair randomization.

In the computer science literature, assigning full voting power to a random fraction of the population is known as *Random Sample Voting (RSV)*.[23] Chaum (2016) suggested such a voting procedure and proposed a protocol for implementing RSV which ensures random voter selection, non-manipulability, verifiability, and anonymity. Subsequently, Basin et al. (2018) have developed a provably secure protocol for RSV. Both protocols could be adapted to our mechanisms. Our paper shows that when coupled with schemes that ensure payments, RSV can yield good decisions even if citizens must exert effort to become informed.

7. Extensions

In this section, we analyze some extensions of our baseline setup in Section 3 and discuss how they affect the results obtained in Section 4.

7.1. Asymmetric priors

Let us assume that the *ex ante* probability that A is the right alternative is p, with $p \in [1/2, 1)$. In our baseline setup, we have assumed $p = 1/2$. In general, if committee member i receives a signal of quality $\frac{1}{2} + x_i$, which comes at private cost $c(x_i)$, the posteriors that alternative A is the right alternative are as follows: If the private signal that citizen i receives is A,

$$Prob\Big[w = A \Big| s_i = A\Big] = \frac{y_i \cdot p}{y_i \cdot p + (1 - y_i) \cdot (1 - p)},$$

where $y_i := 1/2 + x_i$. If the private signal that citizen i receives is B,

$$Prob\Big[w = A \Big| s_i = B\Big] = \frac{(1 - y_i) \cdot p}{y_i \cdot (1 - p) + (1 - y_i) \cdot p}.$$

We note that for $p = \frac{1}{2}$, $Prob\Big[w = A \Big| s_i = A\Big] = y_i$ and $Prob\Big[w = A \Big| s_i = B\Big] = 1 - y_i$. For our analysis of asymmetric priors, we assume informative voting. That is, committee members vote for implementing alternative A (alternative B) if their posterior in favor of alternative A (alternative B) is higher than $1/2$, with ties being broken in favor of the private signal. This means that if committee member i receives signal A, s/he votes for alternative A. By contrast, if committee member i receives signal B, s/he votes for alternative B if and only if $x_i \geq p - \frac{1}{2}$.

The consequences of the above remarks are the following: First, if committee member i chooses quality signal $x_i \in [0, 1/2]$ such that

$$x_i < p - \frac{1}{2},$$

s/he always votes for A, no matter the signal received. Because signals are costly, this means that acquiring any such information level is dominated (in expected terms) by acquiring zero information. Second, if committee member i chooses quality signal $x_i \in [0, 1/2]$ such that

[23] A recent paper by Meir et al. (2021) studies the performance of randomly selected committees of representatives with arbitrary population size that must vote on a number of binary issues.

$$x_i \geq p - \frac{1}{2},$$

then s/he always follows the recommendation of the signal. As far as the analysis of our (family of) mechanisms is concerned, this means that the actual action space for committee member i is

$$\{0\} \cup \left[p - \frac{1}{2}, \frac{1}{2}\right],$$

instead of $[0, 1/2]$. Accordingly, if full information acquisition is the only symmetric equilibrium of the underlying game with symmetric priors, it is also a symmetric equilibrium with asymmetric priors (but other symmetric equilibria may exist). This property can be directly applied for the mechanisms that use the TS analyzed in Section 4.1 where full information is attainable.

Now consider that there is a unique interior symmetric equilibrium $(x, \ldots, x)$ with symmetric priors and $0 < x < 1/2$. Then, it is an equilibrium for asymmetric priors too, provided that $x \geq p - 1/2$. The latter condition holds, therefore, if priors are not very asymmetric. If $x < p - 1/2$, by contrast, either $(0, \ldots, 0)$ or $(p - 1/2, \ldots, p - 1/2)$ are candidates for a symmetric equilibrium, depending on $c(x)$.[24]

For the mechanisms that use the different TS analyzed in Section 4, the probability that the right alternative is implemented is one (when full information is attainable, see Section 4.1) or arbitrarily close to one if we increase committee size m sufficiently (when full information is not attainable, see Section 4.2). In such cases, the equilibrium probability of a tie must either be zero or converge to zero with m. Therefore the incentives related to vote pivotality vanish in equilibrium and under individual deviations, and only those associated with the TS survive. This means that, provided the rewards given to committee members for attaining large majorities are sufficiently large (given the value of p), symmetric equilibria may exist with information acquisition levels that are at least $p - 1/2$.

7.2. Asymmetric preferences

Suppose that for any individual i of the population, utilities when alternatives A or B are implemented are the following:

$$U_i(A|w = A) = 1 \quad \text{and} \quad U_i(B|w = A) = 0,$$

while

$$U_i(B|w = B) = \theta \quad \text{and} \quad U_i(A|w = B) = 0,$$

where $\theta \in (0, 1]$. That is, the error of choosing alternative B when A is the right alternative is equally serious as or more serious than choosing alternative A when B is the right alternative. In the baseline setup, we have assumed $\theta = 1$, i.e., both error types are equally serious.

Suppose now that some individual i's belief that A is the right alternative is ρ, with $\rho \in [0, 1]$. Then s/he (individually) prefers to choose alternative A if and only if

$$\rho \cdot 1 + (1 - \rho) \cdot 0 \geq \rho \cdot 0 + (1 - \rho) \cdot \theta,$$

which can be rearranged as

$$\rho \geq \frac{\theta}{1 + \theta} := \theta^*.$$

The parameter θ^* is usually called the *(individual) threshold of reasonable doubt* (Feddersen and Pesendorfer, 1998). If $\theta = 1$, we have $\theta^* = 1/2$. If $\theta = 0$, we have $\theta^* = 0$.

To see how our results depend on the value of θ^* (or θ), we maintain our focus on symmetric equilibria. Let $(x, \ldots, x)$, with $x \in (0, 1/2)$, be a strategy profile in which all citizens choose information level x.[25] Then for any committee member i, the benefits linked to pivotality (i.e., excluding side-payments) when s/he chooses x_i and everybody else chooses x are

$$\frac{1}{2} \cdot P_x[\text{tie}|w = A] \cdot \left(\frac{1}{2} + x_i\right) + \frac{1}{2} \cdot P_x[\text{tie}|w = B] \cdot \left(\frac{1}{2} + x_i\right) \cdot \theta.$$

Given that the probability of a tie is the same in both states of the world, the above expression can be rewritten as

$$\frac{1}{2(1 - \theta^*)} \cdot P_x[\text{tie}] \cdot \left(\frac{1}{2} + x_i\right).$$

[24] In general it could be the case that neither of the two strategy profiles is an equilibrium.

[25] For full information equilibria, there are no incentives linked to pivotality if the committee consists of at least three members. This means that asymmetric preferences have no bearing on our results in such cases.

To see the effect of introducing $\theta \neq 1$ on equilibrium behavior, note that doing so is equivalent to having each individual care equally about the right alternative in both states of the world, considering cost function

$$\hat{c}(x) = 2(1-\theta^*) \cdot c(x)$$

and TS

$$\hat{t}^m(k) = 2(1-\theta^*) \cdot t^m(k) \text{ for all } k \in \mathcal{D}_m. \tag{19}$$

This follows from (4). Hence, lower reasonable doubts—i.e., lower values of θ^*—do not affect information acquisition levels when the TS considered in Section 4 are used, provided we adjust the reward schemes in accordance with (19).

7.3. Private values

Suppose that an individual can be of three types, A-partisan, B-partisan, and non-partisan. Assuming that types are private, let p_A (p_B) be the *ex ante* probability that an individual is A-partisan (B-partisan), while an individual is non-partisan with probability $1 - p_A - p_B$. The *ex ante* distribution of types is assumed to be common knowledge. Partisan voters always vote for their preferred alternative, so they do not acquire any information because doing so is costly. For our analysis, we assume that members of the committee are randomly chosen from the population. Then, from the perspective of a committee member i who is non-partisan, the probability that all other members of the committee yield a tie (assuming that non-partisans choose information acquisition level x) is

$$\begin{aligned} P_x[pivotal] = &\sum_{\substack{0\le n_A,n_B\le m\\ 0\le n_A+n_B\le 2m}} \frac{F(n_A,n_B,p_A,p_B)}{2}\cdot\left(\frac{1}{2}+x\right)^{m-n_A}\cdot\left(\frac{1}{2}-x\right)^{m-n_B}\\ &+\sum_{\substack{0\le n_A,n_B\le m\\ 0\le n_A+n_B\le 2m}} \frac{F(n_A,n_B,p_A,p_B)}{2}\cdot\left(\frac{1}{2}-x\right)^{m-n_A}\cdot\left(\frac{1}{2}+x\right)^{m-n_B}, \end{aligned}$$

where

$$F(n_A,n_B,p_A,p_B) := \binom{2m}{n_A}\cdot\binom{2m-n_A}{n_B}\cdot p_A^{n_A}\cdot p_B^{n_B}\cdot(1-p_A-p_B)^{2m-n_A-n_B}\cdot\binom{2m-n_A-n_B}{m-n_A}.$$

Accordingly,

$$P_x[pivotal] = G(n_A,n_B,p_A,p_B,x)\cdot\binom{2m}{m}\cdot\left(\frac{1}{4}-x^2\right)^m,$$

where

$$\begin{aligned} &G(n_A,n_B,p_A,p_B,x)\\ :=&\frac{1}{\binom{2m}{m}}\cdot\sum_{\substack{n_A,n_B\\ 0\le n_A+n_B\le 2m}}\frac{F(n_A,n_B,p_A,p_B)}{2}\left(\left(\frac{1}{2}+x\right)^{-n_A}\left(\frac{1}{2}-x\right)^{-n_B}+\left(\frac{1}{2}-x\right)^{-n_A}\left(\frac{1}{2}+x\right)^{-n_B}\right). \end{aligned}$$

One can verify that for $m \geq 1$, $P_{\frac{1}{2}}[pivotal] = 0$ if $p_A = p_B = 0$, while $P_{\frac{1}{2}}[pivotal] > 0$ if $p_A, p_B > 0$. (Recall that $x = 1/2$ means full information acquisition.) Hence, introducing partisan voters increases the chances that an equilibrium with full information acquisition exists, all else being equal (and using the majority rule). This is because partisan voters introduce new incentives to become informed that are linked to pivotality. Assessing whether other equilibria can be introduced with partisan voters would require further analyses.

8. Conclusion

We have analyzed how acquisition of costly information can be fostered through voting with the majority rule in a common-value setup in which some of the parameters and variables of the problem cannot be used in contracts. The main novelty of our approach is that we have simultaneously introduced monetary transfers and vote delegation to a committee formed from a parent body, say, the electorate. Our main insight is that if it is possible to reward committee members, then it might be generally better to delegate information acquisition and voting rights to small committees instead of the entire electorate.

Appendix

Proof of Proposition 1. Consider any committee member i. Then suppose that all other $2m$ members of the committee acquire precise information about the right alternative, that is, they all choose information level $x = 1/2$. Recall that we consider a TS defined by $\phi^m(m) = r$ and $\phi^m(l) = 0$ if $l < m$. Then, since $m \geq 1$, individual i's utility simplifies to (see Equation (3))

$$U_i(x_i) = \left(\frac{1}{2} + x_i\right) \cdot r - c(x_i).$$

Note that $m \geq 1$ guarantees that the committee consists of at least three members, so individual i is not pivotal in the voting round because the other two committee members are perfectly informed and thus vote for the same alternative. Then,

$$U_i'(x_i) = r - c'(x_i) \geq r - c'\left(\frac{1}{2}\right) \geq 0,$$

where the first inequality holds because $c(x)$ is a convex function and the second inequality holds if and only if

$$r \geq c'\left(\frac{1}{2}\right).$$

Hence, as long as the above inequality holds the derivative of $U_i(x_i)$ with respect to x_i is positive in the interval $[0, 1/2]$, so $U_i(x_i)$ is maximized for $x^* = \frac{1}{2}$. This means that in the equilibrium, individual i acquires full information. □

Proof of Theorem 1. Recall that we focus on the case $m \geq 1$. Consider some committee member i, and let all the other $2m$ members of the committee use strategy $x \in [0, 1/2]$, as demanded by our notion of symmetric equilibrium. Then individual i's expected utility when s/he chooses $x_i \in [0, 1/2]$ is

$$\begin{aligned} U_i(x_i) = &\binom{2m}{m} \cdot \left(\frac{1}{2} + x\right)^m \left(\frac{1}{2} - x\right)^m \left(\frac{1}{2} + x_i\right) - c(x_i) \\ &+ \left(\frac{1}{2} + x\right)^{2m} \left(\frac{1}{2} + x_i\right) \cdot \frac{4^{m-1}}{2m} r_m + \left(\frac{1}{2} - x\right)^{2m} \left(\frac{1}{2} - x_i\right) \cdot \frac{4^{m-1}}{2m} r_m + \chi. \end{aligned} \tag{20}$$

We stress that $r_m \geq 0$ is some constant that depends on m (to be determined below) which is independent of x. Recall that χ is independent of x_i by definition. Then, the derivative of $U_i(x_i)$ with respect to x_i is equal to:

$$U_i'(x_i) = \underbrace{\binom{2m}{m} \cdot \left(\frac{1}{2} + x\right)^m \left(\frac{1}{2} - x\right)^m + \frac{4^{m-1}}{2m} r_m \cdot \left[\left(\frac{1}{2} + x\right)^{2m} - \left(\frac{1}{2} - x\right)^{2m}\right]}_{:= D_m(x)} - c'(x_i). \tag{21}$$

Since, by assumption, $c'(0) = 0$, then

$$U_i'(0) = \binom{2m}{m} \cdot \left(\frac{1}{2}\right)^{2m} - c'(0) = \binom{2m}{m} \cdot \left(\frac{1}{2}\right)^{2m} > 0.$$

This means that the (symmetric) strategy profile where committee members acquire no information cannot be an equilibrium. If there is an (interior) symmetric equilibrium defined by x_m^* with less than full information acquisition, i.e., if

$$0 < x_m^* < \frac{1}{2}, \tag{22}$$

then it must be the case that $U_i'(x_m^*) = 0$, or, equivalently, that

$$D_m(x_m^*) = c'(x_m^*). \tag{23}$$

Now let $y_m^* \in (0, 1/2)$ denote the (interior) equilibrium information acquisition level if there are no rewards, i.e. if $r_m = 0$, namely

$$\binom{2m}{m} \cdot \left(\frac{1}{2} - y_m^*\right)^m \left(\frac{1}{2} + y_m^*\right)^m = c'(y_m^*). \tag{24}$$

From the regularity assumptions made on $c(x)$, we know that y_m^* is well-defined and unique. Then note that for all $x < y_m^*$,

$$D_m(x) - c'(x) \geq \binom{2m}{m} \cdot \left(\frac{1}{2}+x\right)^m \left(\frac{1}{2}-x\right)^m - c'(x)$$
$$> \binom{2m}{m} \cdot \left(\frac{1}{2}+y_m^*\right)^m \left(\frac{1}{2}-y_m^*\right)^m - c'(y_m^*) = 0,$$

where the first inequality holds since $r_m \geq 0$ and $x \geq 0$, and the second inequality holds because $c'(x)$ is a strictly increasing function. Note that for the second inequality we have used the fact that

$$\binom{2m}{m} \cdot \left(\frac{1}{2}+x\right)^m \left(\frac{1}{2}-x\right)^m = \binom{2m}{m} \cdot \left(\frac{1}{2}-x^2\right)^m$$

is decreasing for $x \in [0, 1/2]$. To sum up, $u'(x_i) > 0$ on $[0, y_m^*)$, and thus it must be the case that

$$x_m^* \geq y_m^*. \tag{25}$$

Moreover, for all $x \in [0, 1/2]$,

$$D_m(x) \geq \frac{4^{m-1}}{2m} r_m \cdot \left[\left(\frac{1}{2}+x\right)^{2m} - \left(\frac{1}{2}-x\right)^{2m}\right] = 2\frac{4^{m-1}}{2m} r_m \cdot \left(\sum_{j=0}^{m-1} \binom{2m}{2j+1} \cdot \left(\frac{1}{2}\right)^{2(m-j)-1} x^{2j+1}\right)$$
$$\geq 2\frac{4^{m-1}}{2m} r_m \cdot \frac{2m}{2^{2m-1}} \cdot x = r_m \cdot x. \tag{26}$$

Next, define s_m such that

$$s_m \in \arg \max_{\frac{1}{2} \geq q \geq y_m^*} \frac{c'(q)}{q}$$

and

$$s_m \leq y \text{ for all } y \in \arg \max_{\frac{1}{2} \geq q \geq y_m^*} \frac{c'(q)}{q}.$$

Due to the assumptions on $c(x)$ and the fact that $y_m^* > 0$, it must be the case that s_m is well-defined and unique. From (25) and the definition of s_m, it follows, in particular, that

$$\frac{c'(x_m^*)}{x_m^*} \leq \frac{c'(s_m)}{s_m}. \tag{27}$$

Similarly to the proof of monotonicity of the equilibrium information level as in Martinelli (2006), one can verify that y_m^* decreases with m (and converges to zero), and hence s_m also decreases with m. This means that $(s_m)_{m=1}^{\infty}$ has a limit, which we denote by s. We recall that it must always be the case that $n \geq m$, i.e., the number of citizens is at least as large as the number of committee members. If $s > 0$, then for any integer $m \geq 1$,

$$\frac{c'(s_m)}{s_m} \leq \frac{c'(s)}{s} < \infty.$$

If $s = 0$, then for any integer $m \geq 1$,

$$\frac{c'(s_m)}{s_m} \leq \lim_{s' \to 0} \frac{c'(s')}{s'} = c''(0) < \infty,$$

where the latter inequality holds by assumption. In either case, the sequence

$$\left(\frac{c'(s_m)}{s_m}\right)_{m \geq 1}$$

is bounded from above by a constant that depends only on the cost function $c(\cdot)$.
Finally, let

$$r_m := \frac{c'(s_m)}{s_m}.$$

From (21), (22), and (26), we obtain

$$D_m(x_m^*) \geq r_m \cdot x_m^* = x_m^* \cdot \frac{c'(s_m)}{s_m} \geq c'(x_m^*).$$

However, this contradicts (23). Hence, there cannot be a symmetric equilibrium in which committee members inform themselves partially. It therefore remains to show that $x_m^* = 1/2$ is an equilibrium. This follows from Proposition 1 if we define

$$\phi^m(m) := \max\left\{r_m, c'\left(\frac{1}{2}\right)\right\}$$

and

$$\phi^m(-1) = t^m(1) := 0. \quad \square$$

Proof of Proposition 2. Let $l' \in \{2, \dots, m-1\}$, so we assume that $m > 2$. From (4), we know that the strategy profile $(x, \dots, x)$, with $x \in (0, 1/2)$, is an equilibrium of game $\mathcal{G}^m$ only if

$$\begin{aligned} c'(x) = &\binom{2m}{m} \cdot \left(\frac{1}{4} - x^2\right)^m \\ &+ \phi^m(m) \cdot \left[\left(\frac{1}{2} + x\right)^{2m} - \left(\frac{1}{2} - x\right)^{2m}\right] \\ &+ \binom{2m}{m+l'} \cdot \phi^m(l') \cdot \left(\frac{1}{4} - x^2\right)^{m-l'} \cdot \left[\left(\frac{1}{2} + x\right)^{2l'} - \left(\frac{1}{2} - x\right)^{2l'}\right], \end{aligned} \tag{28}$$

where

$$\phi^m(m) = c'(1/2),$$

and we let

$$\phi^m(l') = z_\ell,$$

where $\ell \geq 1$. We assume that $(z_\ell)_{\ell \geq 1}$ is any increasing sequence such that

$$\lim_{\ell \to \infty} z_\ell = \infty, \tag{29}$$

and that (28) has a solution for each $\ell \geq 1$, which we denote by x_ℓ, with $x_\ell \in (0, 1/2)$. Then

$$\begin{aligned} \underbrace{\lim_{\ell \to \infty} c'(x_\ell)}_{:=L_0} = &\underbrace{\lim_{\ell \to \infty} \binom{2m}{m} \cdot \left(\frac{1}{4} - x_\ell^2\right)^m}_{:=L_1} \\ &+ \underbrace{\lim_{\ell \to \infty} \phi^m(m) \cdot \left[\left(\frac{1}{2} + x_\ell\right)^{2m} - \left(\frac{1}{2} - x_\ell\right)^{2m}\right]}_{:=L_2} \\ &+ \underbrace{\lim_{\ell \to \infty} \binom{2m}{m+l'} \cdot \phi^m(l') \cdot \left(\frac{1}{4} - x^2\right)^{m-l'} \cdot \left[\left(\frac{1}{2} + x_\ell\right)^{2l'} - \left(\frac{1}{2} - x_\ell\right)^{2l'}\right]}_{:=L_3}. \end{aligned} \tag{30}$$

Clearly, $L_0, L_1, L_2, L_3 \geq 0$. On the one hand, assume that

$$\lim_{\ell \to \infty} x_\ell = x_L > 0. \tag{31}$$

Then, by our regularity assumptions,

$$L_0 = c'(x_L) < \infty,$$

which implies

$$L_3 < \infty.$$

Due to (31),

$$\lim_{\ell \to \infty} \left[\left(\frac{1}{2} + x_\ell\right)^{2l'} - \left(\frac{1}{2} - x_\ell\right)^{2l'}\right] = \left[\left(\frac{1}{2} + x_L\right)^{2l'} - \left(\frac{1}{2} - x_L\right)^{2l'}\right] > 0,$$

so it must be the case that

$$\lim_{\ell\to\infty} z_\ell \cdot \lim_{\ell\to\infty}\left(\frac{1}{4}-x_\ell^2\right)^{m-l'} < \infty.$$

A necessary condition for the above inequality to hold is

$$\lim_{\ell\to\infty}\left(\frac{1}{4}-x_\ell^2\right)^{m-l'} = 0,$$

which holds only if

$$x_L = \frac{1}{2}.$$

But this implies

$$L_0 = c'\left(\frac{1}{2}\right) < c'\left(\frac{1}{2}\right) + \varepsilon \le L_1 + L_2 + L_3,$$

which is in contradiction to (30). On the other hand, assume that

$$\lim_{\ell\to\infty} x_\ell = x_L = 0.$$

Since $c'(0) = 0$,

$$0 = L_0 < \binom{2m}{m}\cdot\left(\frac{1}{4}\right)^m = L_1 \le L_1 + L_2 + L_3,$$

which is also in contradiction to (30). That is, we have proved that a sequence $(z_\ell)_{\ell\ge 1}$ with the properties imposed above cannot exist. This means that if $\phi^m(l')$ is sufficiently large, there is no symmetric equilibrium in which individuals choose $x \in (0, 1/2)$. Since $c'(0) = 0$, we also know that there is no equilibrium in which no information is acquired. Finally, Theorem 1 guarantees that full information can be sustained in equilibrium. This completes the proof of the proposition. □

Proof of Theorem 2. From (4) and (14) we know that the strategy profile $(x, \ldots, x)$, with $x \in (0, 1/2)$, is an equilibrium of game $\mathcal{G}^m$ if and only if

$$c'(x) = \binom{2m}{m}\cdot\left(\frac{1}{4}-x^2\right)^m + \binom{2m}{m+1}\cdot\phi^m(1)\cdot\left(\frac{1}{4}-x^2\right)^{m-1}\cdot 2x, \tag{32}$$

where $\phi^m(1)$ is a constant that will be determined below and which does not depend on x. Since $c'(0) = 0$ and $c'(1/2) = \infty$, there is no equilibrium with zero information acquisition and/or with full information acquisition for any $m \ge 1$. Also for any $m \ge 1$, there is (at least) one equilibrium, since the first order condition (32) always has a positive solution. For $x = 0$, the left-hand side of Equation (32) is 0 and the right-hand side is positive. For $x = \frac{1}{2}$, the left-hand side of Equation (32) is ∞ and the right-hand side is finite. We let henceforth $(x_m)_{m\ge 1}$ be any sequence where for any positive integer m, x_m is a solution of Equation (32).

The remainder of the proof proceeds in several steps. First, suppose that for *all* sufficiently large committee sizes m,

$$x_m \ge \underline{x}_m := \sqrt{\frac{d_m \log m}{m}}, \tag{33}$$

for some sequence $(d_m)_{m\ge 0}$, with $d_m > 0$ for all $m \ge 1$. The values for d_m will be specified below. We claim that if the elements of the sequence $(d_m)_{m\ge 0}$ are chosen to be sufficiently low but positive, the probability of the right alternative being implemented goes to one as committee size m grows unboundedly, i.e.,

$$\lim_{m\to\infty} Q_m(x_m) = 1. \tag{34}$$

Clearly, because $Q_m(x)$ is increasing in x (for a given m), it suffices to prove the claim for a boundary case, that is, it suffices to assume $x_m = \underline{x}_m$ for sufficiently large m (see below). To show the claim, for any $m \ge 1$, let $X_1, \cdots, X_{2m+1}$ be i.i.d. Bernoulli random variables with parameter $\frac{1}{2} + \underline{x}_m$. In addition, define the following random variable:

$$S_m := \sum_{l=1}^{2m+1} X_l.$$

Then the probability that the right alternative is *not* implemented is equal to

$$P\left[S_m \le m\right].$$

By linearity of expectation,

$$\mathbb{E}(S_m) = (2m+1) \cdot \left(\frac{1}{2} + \underline{x}_m\right), \tag{35}$$

so

$$m - \mathbb{E}(S_m) = m - (2m+1) \cdot \left(\frac{1}{2} + \underline{x}_m\right) < -2m \cdot \underline{x}_m < 0. \tag{36}$$

Then,

$$\begin{aligned} P[S_m \le m] &\le P\left[S_m - \mathbb{E}(S_m) \le -2m \cdot \underline{x}_m\right] \le P\left[\left|S_m - \mathbb{E}(S_m)\right| \ge 2m \cdot \underline{x}_m\right] \\ &\le 2\exp\left(-\frac{2\left(2m \cdot \underline{x}_m\right)^2}{2m+1}\right) = 2\exp\left(-\frac{8m^2}{2m+1} \cdot \left(\frac{d_m \log m}{m}\right)\right) \le 2\delta m^{-\varepsilon}, \end{aligned}$$

for any $\delta > 1$, where the second inequality holds due to (35) and (36), the third inequality is Hoeffding's inequality (see Hoeffding, 1963), the equality in the above expression follows from the definition of $\underline{x}_m$ (see (33)), and the last inequality is explained as follows: Given $\varepsilon > 0$, there is a large enough $m^*(\varepsilon)$, such that if we let

$$d_m = d := \frac{\varepsilon}{4}, \text{ for all } m \ge m^*(\varepsilon), \tag{37}$$

it must be the case that

$$m^{\varepsilon} \le \delta \exp\left(\frac{8m^2}{2m+1} \cdot \left(\frac{d \log m}{m}\right)\right) \text{ for any } m \ge m^*(\varepsilon). \tag{38}$$

This is because

$$\lim_{m\to\infty} \frac{\exp\left(\frac{8m^2}{2m+1} \cdot \left(\frac{d \log m}{m}\right)\right)}{m^{\varepsilon}} = \lim_{m\to\infty} \frac{m^{4d}}{m^{\varepsilon}} = 1.$$

We have therefore proved that the above claim is correct: It suffices to take $\varepsilon \to 0$.

Next, we prove the lower bound on the acquired information given by Inequality (33). To do so, first we show the following technical derivation:

$$\begin{aligned} &\lim_{m\to\infty} \frac{\left(\frac{1}{4} - \frac{d_m \log m}{m}\right)^{m-1}}{\left(\frac{1}{4}\right)^{m-1}} m^{\varepsilon} \\ &= \lim_{m\to\infty} \left(1 - \frac{4d_m \log m}{m}\right)^{m-1} m^{\varepsilon} \\ &= \lim_{m\to\infty} \left(1 - \frac{4d_m \log m}{m}\right)^{m} \cdot \lim_{m\to\infty} \left(1 - \frac{4d_m \log m}{m}\right)^{-1} m^{\varepsilon} \\ &= \lim_{m\to\infty} \left(1 - \frac{4d_m \log m}{m}\right)^{m} m^{\varepsilon} = \lim_{m\to\infty} \left(1 - \frac{4d_m \log m}{m}\right)^{\frac{m}{4d_m \log m} \cdot 4d_m \log m} m^{\varepsilon} \\ &= \lim_{m\to\infty} \left(\frac{1}{e}\right)^{4d_m \log m} m^{\varepsilon} = \lim_{m\to\infty} m^{-4d_m} m^{\varepsilon} = 1. \end{aligned} \tag{39}$$

On the other hand, by applying Stirling's approximation,

$$\begin{aligned} \lim_{m\to\infty} \binom{2m}{m+1} \left(\frac{1}{4}\right)^{m-1} &= \lim_{m\to\infty} \frac{(2m)!}{(m+1)!(m-1)!} \left(\frac{1}{4}\right)^{m-1} \\ &= \lim_{m\to\infty} \sqrt{\frac{m}{m^2-1}} \cdot \frac{m^{2m}}{(m+1)^{m+1}(m-1)^{m-1}} \\ &= \lim_{m\to\infty} \frac{1}{\sqrt{m}}, \end{aligned} \tag{40}$$

where we ignored constant factors since the limit is equal to 0.

By combining (39) and (40), we obtain

$$\lim_{m\to\infty}\binom{2m}{m+1}\left(\frac{1}{4}-\frac{d_m\log m}{m}\right)^{m-1}=\lim_{m\to\infty}\binom{2m}{m+1}\left(\frac{1}{4}\right)^{m-1}\cdot\lim_{m\to\infty}\frac{\left(\frac{1}{4}-\frac{d_m\log m}{m}\right)^{m-1}}{\left(\frac{1}{4}\right)^{m-1}}$$
$$=\lim_{m\to\infty}m^{-\varepsilon}\cdot\lim_{m\to\infty}\frac{1}{\sqrt{m}}$$
$$=\lim_{m\to\infty}\frac{1}{m^{\frac{1}{2}+\varepsilon}},\tag{41}$$

where we ignored constant factors since the limit is equal to 0.

Finally, for each $\varepsilon>0$, let

$$\phi^m(1):=\frac{c'(s_m)}{s_m}\cdot m^{\frac{1}{2}+\varepsilon}$$

where

$$s_m\in\arg\max_{q\leq\underline{x}_m}\frac{c'(q)}{q}$$

and

$$s_m\leq y\text{ for all }y\in\arg\max_{q\leq\underline{x}_m}\frac{c'(q)}{q}.$$

In particular, it must be the case that

$$\frac{c'(\underline{x}_m)}{\underline{x}_m}\leq\frac{c'(s_m)}{s_m}<\infty.\tag{42}$$

The strict inequality holds because

$$\lim_{s\to 0}\frac{c'(s)}{s}=c''(0)<\infty.$$

Then,

$$\lim_{m\to\infty}\binom{2m}{m}\cdot\left(\frac{1}{4}-x_m^2\right)^m+\binom{2m}{m+1}\cdot\phi^m(1)\cdot\left(\frac{1}{4}-x_m^2\right)^{m-1}\cdot 2x_m$$
$$\geq\lim_{m\to\infty}\binom{2m}{m+1}\cdot\left(\frac{1}{4}-x_m^2\right)^{m-1}\cdot 2\lim_{m\to\infty}m^{\frac{1}{2}+\varepsilon}\cdot\lim_{m\to\infty}\frac{c'(s_m)}{s_m}\cdot x_m$$
$$\geq\lim_{m\to\infty}\binom{2m}{m+1}\cdot\left(\frac{1}{4}-x_m^2\right)^{m-1}\cdot 2\lim_{m\to\infty}m^{\frac{1}{2}+\varepsilon}\cdot 2\lim_{m\to\infty}c'(\underline{x}_m)$$
$$=\frac{4}{\sqrt{\pi}}\cdot\lim_{m\to\infty}c'(\underline{x}_m)>\lim_{m\to\infty}c'(\underline{x}_m),\tag{43}$$

where the second inequality holds by (42) and the equality holds by (41). However, (43) contradicts the fact that x_m satisfies (32) for sufficiently large m. That is, for any $m\geq m^*(\varepsilon)$, it must be the case that

$$x_m\geq\underline{x}_m.$$

Taking $\varepsilon\to 0$ and using Equation (34) completes the proof of the theorem. □

Proof of Theorem 3. Here we focus on the decision of the second voting round, in which $2n-2m$ individuals vote after the outcome of the first voting round (by the committee) has been made public. We let d denote the *difference* in votes that alternative A received from the committee members compared to alternative B. Note that d is an odd number (assuming all committee members vote) and that it may be positive or negative ($d\in\mathcal{D}_m$). This means that in the second voting round, alternative B must receive at least $d+1$ more votes than alternative A if it is to be implemented. As in the first voting round, we focus on symmetric equilibrium in the second round. That is, we assume that all individuals acquire the same level of information $x^{**}(n)\in[0,1/2]$ and that, conditional on the signal they obtain (and given their posterior q obtained after the first voting round), they vote for the same alternative (with probability one). We also assume that there is no abstention in the second round and that

$$2n - 2m \geq 2m + 4, \tag{44}$$

which is clearly satisfied if n is large enough. Condition (44) ensures that individuals who are not members of the committee can undo any decision taken by members of the committee (for appropriate voting behavior which does not require unanimity). Without loss of generality, we assume that $d > 0$, and hence $q > 1/2$. That is, A received more votes in the first round and individuals with the right to vote in the second round believe that alternative A is the right alternative with probability larger than 1/2.

Recall that if $x < 1/2$, in equilibrium all individuals in the second round must equate the pivotal probability with the increases in disutility derived from acquiring more information than x—see Equation (4). We distinguish two cases. First, assume that given x, m, d, and q, all voters in the second round vote for the same alternative. Due to (44), no single individual is pivotal. Therefore, it must be the case that $x = 0$. This means that individuals voting in the second round receive no informative signal, so the only voting behavior that is consistent with equilibrium is to vote according to the posterior $q > \frac{1}{2}$ in favor of alternative A.

Second, assume that given x, m, d, and q, voters in the second round vote for both alternatives, depending on the signal. That is, those who receive an A signal vote for alternative A, and those who receive a B signal vote for alternative B. Now let i denote one individual with the right to vote in the second round. One can easily see that (excluding i's vote) the probability that there is a tie is equal to:

$$P_x[\text{tie}] = q \cdot \left[\binom{2(n-m)-1}{(n-m)-\frac{d+1}{2}} \cdot \left(\frac{1}{2}+x\right)^{(n-m)-\frac{d+1}{2}} \cdot \left(\frac{1}{2}-x\right)^{(n-m)+\frac{d-1}{2}} \right]$$
$$+ (1-q) \cdot \left[\binom{2(n-m)-1}{(n-m)-\frac{d+1}{2}} \cdot \left(\frac{1}{2}-x\right)^{(n-m)-\frac{d+1}{2}} \cdot \left(\frac{1}{2}+x\right)^{(n-m)+\frac{d-1}{2}} \right].$$

One can also verify that for fixed x, m, d, and q,

$$\lim_{n\to\infty} P_x[tie] = 0,$$

since non-degenerate binomial distribution probabilities uniformly converge to 0 when the support size converges to infinity and the success probability parameter is independent of the support size. Hence,

$$\lim_{n\to\infty} x^{**}(n) = 0.$$

Then, using the same logic as in Section 7.1, we can see that if n is sufficiently large, any individual with the right to vote in the second round believes that A is the right alternative with probability higher than 1/2, given the posterior q and his/her own signal of accuracy $x^{**}(n) \approx 0$. This is because $q > 1/2$ is independent of n. But this contradicts the assumption that individuals acquire positive levels of information in equilibrium.

To sum up, for large n, in any equilibrium of the game underlying AV, it must be the case that all individuals in the second round acquire zero information and simply vote for the alternative that received more votes in the committee voting round, provided that its members chose a positive level of information. □

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