Sequential Deliberation

Alessandro Lizzeri* Leeat Yariv†‡

November 4, 2010

Abstract. We present a dynamic model of deliberation in which 'jurors' decide every period whether to continue deliberation, which generates costly information, or stop and take a binding vote yielding a decision. For homogeneous juries, the model is a reinterpretation of the classic Wald (1947) sequential testing of statistical hypotheses. In heterogeneous juries, the resources spent on deliberation depend on the jury's preference profile. We show that voting rules at the decision stage are inconsequential when either information collection is very cheap or deliberation agendas are strict enough. Furthermore, wider preference distributions, more stringent deliberation agendas, or more unanimous decision voting rules, lead to greater deliberation times and more accurate decisions.

Keywords: Deliberation, Voting, Juries

*Department of Economics, NYU. E-mail: alessandro.lizzeri@nyu.edu

†Division of the Humanities and Social Sciences, Caltech. E-mail: lyariv@hss.caltech.edu

‡We thank Nicola Persico, Debraj Ray, and Nikita Roketskiy for comments and suggestions. We gratefully acknowledge financial support from the National Science Foundation (SES 0551014) and the Gordon and Betty Moore Fooundation.

1. Introduction

1.1 Overview

Decision making in groups often involves deliberation. Juries, boards of directors, congressional and university committees, government agencies such as the FDA or the EPA, and many other committees, spend time deliberating issues before reaching a decision or issuing a recommendation. This paper presents a simple model of deliberation to study the effect of the structure of the deliberative process, and of the composition of deliberating groups, on outcomes such as the accuracy of decisions, the length of deliberation, and the degree of disagreement.

Previous literature on deliberation has focused on asymmetric information among members of the deliberating group, on how this information asymmetry can impede effective decision making, and how different voting rules interact with this information asymmetry.[1] We abstract from private information and focus on a simpler aspect of collective action: how information collection responds to conflicting preferences. In a deliberating committee, there are two types of decisions to make: *deliberation decisions* and *action decisions*. Deliberation decisions are about whether to keep deliberating in order to obtain additional information. Action decisions regard the choice to be taken at the end of deliberation. Deliberation is in service of action decisions since the information that is obtained is supposed to allow more accurate action decisions.

The focus of this paper is the novel dimension that emerges because of a consideration of sequential deliberation in committees: the distinction between *deliberation rules* and *decision rules*. A deliberation rule governs the deliberation process and determines when information acquisition must stop. A decision rule governs the vote over issues at the end deliberation. There are many examples where deliberation rules are different from decision rules. For instance, in many committees, the chairman of the committee has the same power as all the other members of the committee over action decisions, but has a special role to play (and more power) in deliberation decisions. However, while voting rules are often quite precisely described – some issues requiring a majority vote, others requiring a supermajority or unanimity – deliberation rules are often vague. Despite this vagueness, it is useful to think broadly of committees that have more inclusive deliberation protocols than others. We will initially model this inclusiveness as a threshold rule R_d such that deliberation ends

[1] E.g., Austen-Smith and Feddersen (2005, 2006), Coughlan (2000), Gerardi and Yariv (2007, 2008), Meirowitz (2006), and Persico (2004).

as soon as R_d members of the committee vote to end deliberation. Voting rules are analogously captured by a rule R_v that describes the specific qualified majority required for reaching a decision. Our analysis discusses the effects of deliberation and voting rules on the length of deliberation, the accuracy of decisions, and the welfare of the committee and of society at large. We show that there is a sense in which deliberation rules are more "effective" than voting rules. For instance, we show that under certain assumptions, voting rules are irrelevant, while deliberation rules affect the length of deliberation and accuracy of ultimate decisions. Furthermore, we show that, for a range of parameters for which the voting rule does have an effect, in contrast with Feddersen and Pesendorfer (1998) and Persico (2004), unanimity leads to more informative outcomes than majority rule. We also show that a committee would like to delegate deliberation power to a moderate chairman, consistent with many real-world deliberation formats. Finally, we contrast sequential deliberation with static deliberation and argue that the sequential case displays a richness that is closer to the phenomena that are associated with deliberation.

The formal analysis in this paper is relevant for a variety of collective decision processes. However, we focus much of our discussion on juries. This is for three reasons. First, in juries, the deliberation process is clear-cut and circumscribed: there is a well-defined beginning and end of deliberation, the time it takes the jury to deliberate is measurable, and one single verdict is the typical outcome of such deliberation. Second, juries have been the focus of much prior literature on deliberation so it is useful to relate our framework to the analysis in this prior work. Third, the empirical literature has documented some patterns of deliberation in juries that we will attempt to explain with our model.

Technically, our analysis is a natural extension of much of the analysis of individual decision making to group contexts. Indeed, an important aspect of individual decision making is the appropriate amount of information to acquire before making a decision. An individual must weigh the cost of information against the value of making more accurate decisions. A classic and natural approach to this question, going back to Wald (1947a,b), is that of Bayesian sequential analysis.[2] In this approach an individual acquires information sequentially, and at every stage evaluates whether he has sufficient information to make a decision: if he does, he stops and takes a decision; if he does not, he proceeds to acquire additional information. In that respect, one of the goals of the present paper is to understand how the structure of collective action affects such information acquisition. We use

[2] See also De Groot (1970) and Moscarini and Smith (2001).

the term deliberation for such collective information acquisition.

In fact, our model is a collective action version of the analysis of sequential sampling introduced by Wald (1947a,b). In our model, a homogeneous committee deliberates in a manner that is analogous to the decision maker testing a hypothesis sequentially à la Wald: at every date, the committee evaluates its current information and decides to do one of three things: continue sampling — i.e., continue deliberating, or stop and take one of two decisions. Wald showed that the optimal procedure involves a sequential likelihood ratio test, whereby intermediate values of the likelihood ratio require obtaining a new sample, while high (low) values of the likelihood ratio require stopping and taking one (the other) decision. We depart from Wald by introducing two possible dimensions of disagreement among committee members. The first involves disagreement exclusively on the importance of the decision (or, equivalently, on the cost of information acquisition), and hence on the length of the deliberation process. In this first version, committee members share preferences over decisions conditional on the information available, but disagree on how much information is required before making the decision. The second version involves disagreement on the appropriate decision: for example, some jurors require a higher standard of evidence in order to vote to convict. In this version, there can be disagreement at the deliberation *and* at the decision stage.

We now briefly discuss some evidence from the literature on deliberation in juries that our model can explain and help interpret.

Deliberation matters One strand of the literature studies opinion formation by jurors. This is relevant for our model for two reasons. First, this establishes that the deliberation process is very important in forming jurors' opinions.[3] Second, some features of the opinion formation process seem to mirror the updating process postulated in our model.

Hannaford, Hans, Mott, and Musterman (2000) studied the timing of jury opinion formation. They used a special case study of a jury reform implemented in Arizona in 1995 that allowed for discussions during civil trial (Rule 39(f) of the Arizona Rules of Civil Procedure). Their data includes survey responses of 1,385 jurors from 172 trials in four counties (accounting for a large majority of cases in Arizona) concerning when they formed their initial opinions, whether and when they changed their minds, and when they arrived at a resolution regarding the final outcome. They find that fewer

[3] This is in partial contrast with the prior received wisdom that comes from the Kalven and Zeisel (1966) landmark jury study.

than 10% of jurors began leaning toward one side or the other during the opening statements of a case and over 25% of jurors reported establishing their initial leaning following discussions with other jurors. Furthermore, over 95% of jurors reported changing their mind at least once over the course of the trial and 15% reported changing their minds more than once during trial. Importantly, over 20% reported changing their minds in discussions during the trial and over 40% reported changing their minds during the final deliberations.

Similarly, Hans (2001, 2007) used surveys conducted by the National Center for State Courts (NCSC). Hans' data contains reports from close to 3,500 jurors that had participated in felony trials in four large, urban courts. Hans (2001, 2007) documents patterns of opinion change that are consistent with information collection. When the initial vote in the jury strongly supports a particular outcome, that outcome is more likely to ultimately emerge (77 of the 89 juries with strong majorities for guilt convicted the defendant, and 67 of the 71 juries with strong majorities for innocence acquitted the defendant). However, weaker majorities or closely divided juries show a more variable pattern.[4]

Irrelevance of the decision rule Baldwin and McConville (1989) studied British juries in Birmingham following a reform that was put in place in 1974 and qualified potential jurors. In particular, the reform allowed for majority verdicts in criminal trials, while prior to the reform unanimity was required. They studied details regarding jurors' characteristics and case outcomes pertaining to 326 cases in a 21 months period in 1975 and 1976. In only 15 of these trials did juries determine the verdict with a mere majority.[5] Devine et al. (2001) report that in many mock jury studies there is no evidence that the decision rule has any effect on the verdict. In lab experiments, Goeree and Yariv (2010) find that, when subjects cannot talk before voting, the decision rule has an effect, whereas, when subjects can talk, the decision rule has very little effect.

Our model provides a possible explanation for the fact that the decision rule seems to have little or no effect. We show that, when costs of deliberation are sufficiently low, in equilibrium, deliberation always ends with unanimous decisions: whenever there is disagreement on the appropriate decision to take, members of the committee agree that it is worthwhile to continue deliberating.

[4] These observations should be interpreted with some care, as initial polls within the jury sometimes take place after some amount of deliberations has already taken place. Thus, consensus may be overstated.

[5] A caveat to this observation is that under simple majority, when a majority of jurors agrees, any other juror's vote cannot affect the final outcome. In particular, those jurors may vote against their private assessment to satisfy social pressures at no consequence to the defendant.

Effect on length of deliberation Hans (2001) and Devine et al. (2001) report that the voting rule affects length and quality of deliberation. On average, using mock juries, under unanimity verdicts take as long as under majority. The quality, measured by legal experts, exhibits similar patterns – higher under unanimity than under majority.

In our model, the length of deliberation can be affected by the decision rule since pivotal members at the deliberation stage may, if not pivotal at the decision stage, prolong deliberation in order to convince the holdouts at the decision stage.

Jury composition Increased heterogeneity has been found to increase quality and length of deliberation (Sommers 2006, Goeree and Yariv 2010).

In our model, increased heterogeneity increases the length of deliberation because it makes the pivotal members at the deliberation stage more extreme, and therefore more in need of extreme information in order to stop deliberation. This translates immediately into longer deliberation and, in symmetric committees, more accurate decisions.

1.2 Literature Review

The past two decades have delivered a rich collection of work on committee decision making (see Li and Suen 2009 for an extended survey). Our paper ties directly to several strands of studies.

In terms of jury decision making, our setup can naturally be contrasted with several papers focusing on information aggregation within juries. Feddersen and Pesendorfer (1998) study a model in which jurors have private information about the guilt or innocence of the defendant. They show that unanimity leads to less informative outcomes than does simple majority in large juries. Persico (2004) studies a related model, but also allows for private information collection prior to voting. He characterizes the optimal voting rule and shows that unanimity leads to inferior information collection. Austen-Smith and Feddersen (2006) extend Feddersen and Pesendorfer (1998) in another way by allowing for a round of cheap-talk communication before voting. They show that unanimity leads to less communication and poorer information aggregation. Gerardi and Yariv (2007, 2008) depart from these papers by studying general communication protocols and analyzing the entire set of equilibrium outcomes. They show that the set of equilibrium outcomes is invariant to the voting rules, as long as they are non-unanimous. In fact, unanimous voting rules generate a subset of equilibrium outcomes. With respect to these papers, since one of the messages of our analysis is that more stringent decision rules entail more information collection and more accurate decisions, it implies that understanding the public component of information collection can be crucial for designing welfare enhancing institutions.

Several studies have looked at the effects of sequential collection of information within groups. Albrecht, Anderson, and Vroman (2010) and Compte and Jehiel (2010) study how group search is affected by voting. Messner and Polborn (2009) study a two-period model where voters receive information over time about the desirability of an irreversible decision. The main message of that paper is that the optimal voting rule requires a supermajority. Bognar, Meyer-ter-Vehn, and Smith (2009) also study a model of dynamic deliberation, but with very different ingredients. In their model jurors have common preferences and private information about a payoff relevant state. They assume that jurors sequentially exchange coarse messages. In their model there are many equilibria that can be ranked in terms of generated welfare. Surprisingly, longer conversations are better.[6] Strulovici (2010) analyzes a model of voting over experimentation. He shows that voting by heterogeneous voters, who are learning their preferences, leads to an inefficient level of experimentation. He then describes a voting rule that can restore efficiency.

In comparison to all of this existing work, the main contribution of the framework proposed in this paper is that it allows for an analysis of the interplay between deliberation rules and decision rules. We identify when each plays an important role for outcomes, and how collective consequences are affected by different aspects of the environment (deliberation costs, preference heterogeneity, etc.).

From a technical perspective, the starting point of our analysis is Wald (1947a,b), who pioneered the study of sequential testing, and provided a characterization of the optimal sequential test as a sequential likelihood ratio test. We briefly describe the most directly relevant result in section 3.1.[7]

2. The Model

2.1 Setup

A jury of n individuals has to determine the fate of a defendant. There are two states: I (the

[6] A related paper is that of Eso and Fong (2008), who study a dynamic cheap talk model with multiple senders, where the receiver can choose when to make her decision. They show that when the senders are all informed of the state of nature, a perfect Bayesian equilibrium exists with instantenous, full revelation, regardless of the size and direction of the senders' biases.

[7] Moscarini and Smith (2001) consider a different extension of Wald's analysis, where they allow for simultaneous as well as sequential experimentation, and they assume discounting and convex costs of sample size.

defendant is innocent) and G (the defendant is guilty), which we assume are equally likely ex-ante.[8]

Juror i's preferences are given by:

$$u_i(C,G) = u_i(A,I) = 0, \quad u_i(A,G) = -(1-q_i), \quad u_i(C,I) = -q_i,$$

where q_i denotes juror i's threshold of reasonable doubt (capturing her concern for convicting the innocent relative to that for acquitting the innocent). Without loss of generality, we assume $q_1 \leq q_2 \leq ... \leq q_n$. We assume that $q_1 > 0$ and $q_n < 1$.

In determining the verdict, the jury participates in two phases: deliberation and voting.

We assume that deliberation allows each juror to publicly learn something about the guilt of the defendant. We formalize this collective information generation as follows. If the jurors still deliberate at time t, all observe the realization of the sequence of random variables $X_1, ..., X_t$, where $X_1, X_2, ...$ are independent and identically distributed conditional on the guilt or innocence of the defendant. Each random variable is drawn from an atomless distribution characterized by cumulative distribution functions $F_G(\cdot) \equiv F(\cdot|G)$ when the defendant is guilty and $F_I(\cdot) \equiv F(\cdot|I)$ when the defendant is innocent.[9]

The cost of deliberating an additional period is given by $k > 0$ per unit of time per agent (which can be thought of as the opportunity costs of time spent in court).

At each period, the jury decides whether to continue or stop deliberating using a threshold voting rule. Namely, at each period t, after having observed the history $X_1, ..., X_t$, each agent casts a vote whether to continue or stop information collection. Under *deliberation rule* $R_d = \lceil \frac{n}{2} \rceil, ..., n$, whenever at least R_d jurors choose to stop deliberating, the deliberation phase ends.

Once deliberation comes to a halt, the decision phase takes place. The jury selects an alternative by voting. Each juror can vote to acquit, a, or to convict, c. Under the *decision rule* $R_v = \lceil \frac{n}{2} \rceil, \ldots, n$, the alternative C is selected if and only if R_v or more jurors vote to convict, the alternative A is selected if and only if R_v or more jurors vote to acquit, and the jury is hung otherwise. We assume that when the jury is hung, A or C are determined by the flip of a fair coin.[10] We will restrict

[8] Much of our analysis could be easily extended to the asymmetric case.

[9] Allowing for atoms in the distribution would introduce some technical subtleties in the description of our results and their proofs without any major qualitative differences.

[10] The exact assumption we make about the payoff consequences of hung juries is for the most part inconsequential. Our initial analysis focuses on cases where hung juries do not occur (low costs of deliberation). Section 9.4 discusses the case of hung juries.

attention to strategies that depend only on posterior beliefs p (and not on the history of prior votes). Therefore, a pure strategy is a pair (σ_d, σ_v), where the *deliberation strategy* is $\sigma_d : [0,1] \to \{\text{stop}, \text{continue}\}$ and the *voting strategy* is $\sigma_v : [0,1] \to \{a, c\}$.

Throughout the paper we will only consider equilibria that are composed of strategies that not weakly dominated. This will allow us to rule out standard multiplicity of predictions that arises from, say, all agents voting in consensus at the decision phase (in some or all periods) due to the fact that unilateral deviations do not affect outcomes. For readability purposes, and slightly abusing terminology, we will simply refer to the corresponding set as the set of 'equilibria' (or 'equilibrium' when unique).

For much of our analysis, it is useful to consider deliberation strategies that are characterized by two fixed thresholds for the posterior $p^a \leq 1/2 \leq p^c$. That is, each agent chooses to stop deliberation whenever the timed posterior p_t (that the defendant is guilty) satisfies $p_t \leq p^a$ or $p_t \geq p^c$.[11] We will refer to these thresholds as *deliberation thresholds*.

2.2 Discussion of the model

The model is an extension of Wald (1947a,b) to study how collective action affects information collection. In the model, longer deliberation corresponds to additional signals received by the committee. Our interpretation is that this is a reasonable shortcut for thinking about how deliberation helps jurors gain an understanding of the evidence presented at trial. Of course, in a jury setting, it could be claimed that no additional information is received by the jurors during deliberation. We argue that one role of deliberation is to sift through the mass of sometimes conflicting evidence presented by two opposing parties (prosecution and defense) during the trial to figure out the relevance of different pieces of information, and the appropriate weight to attribute to these in establishing guilt or innocence of the defendant. In a way, the trial is like a lecture given by a professor, and the jury is like a study group that looks through the notes taken during class to gain some further understanding of a problem at hand.

As mentioned above, there are many alternative applications that may fit directly with the model because actual additional signals are received as deliberation continues/information is gathered.

[11] Recall that the prior probability that the defendant is guilty is $1/2$. In particular, choosing a threshold $p^a \geq 1/2$ (or $p^c \leq 1/2$) would lead to no information collection. Our assumption that $p^a \leq 1/2 \leq p^c$ is therefore without loss of generality.

Abstractly, any scenario in which a group gathers information over time regarding two possible courses of action, with a status quo being chosen if the group cannot come to an agreement, shares features with our model. More concretely, in an R&D process, agents receive feedback about the likely success of specific avenues of research; in a drug approval process, the FDA can require additional clinical trials to be performed, and in fact, the FDA approval process is explicitly designed to require several stages of testing; in hiring practices, follow-up interviews can be requested, or additional research into a candidate can be performed; a board of directors can require additional due diligence before proceeding with a merger; and so on and so forth.

We assume that all information in the jury is public: signals are observed by all jurors, and preferences are common knowledge. This assumption represents a sharp departure from much of the extant literature on juries discussed before, where the focus is on the aggregation of private information. We view our model as a natural alternative extreme benchmark that is useful for identifying the tensions that arise in a collective when trading off information collection costs and decision accuracy.[12]

For realism purposes, we focus on supermajoritarian deliberation rules, i.e., $R_d \geq n/2$. Our analysis could easily be extended to deliberation rules $R_d < n/2$. In fact, we use supermajoritarian deliberation rules simply as a way to capture succinctly the effective agenda setters during deliberation and highlight the interplay between these agents and those pivotal during the decision phase. Our analysis could allow for the specification of arbitrary agenda setters in the deliberation phase that do not come about through a vote (as is the case in settings in which, say, a committee chair determines when discussions should come to a halt).

Another restriction, common to many voting models, that we impose is that there are only two actions. It is not easy to extend the analysis to more than two actions. However, we can consider a continuous action version of a simpler model. We discuss this in Section 9.3, where we present a simple model of civil juries.

[12] Introducing private information about preferences (the q's) into the model would also be interesting. In such a setup, behavior during the deliberation phase could serve to signal agents' preferences. Therefore, optimal behavior is unlikely to be stationary in such an environment, making the analysis more complex. We believe such an extension to our setting may offer new insights into sequential information acquisition, but the forces highlighted by our analysis should persist. We return to this point in Section 9.4.

3. PRELIMINARIES

We start by considering a homogenous jury containing agents with the same preference parameter: $q_1 = ... = q_n \equiv q$. In that case, the agents all face the same objective at both phases of the decision process. Consequently, we will focus on equilibria that emulate the single person decision (by, say, voting in unison during both the deliberation and voting stage). In this section we therefore focus on the case in which $n = 1$.[13] From Wald (1947a,b), we know the solution is unique. Formally,

Proposition 1 (Wald, 1947) *There exists a solution* $(p^a(q;k), p^c(q;k))$ *for any* q and k. *Furthermore, whenever there is an interior solution, it is unique.*

While we do not provide the proof of Proposition 1, it is useful for our analysis to illustrate the intuition behind the proposition as it is translated to our setup.[14] Fix the information cost k. For any posterior probability p, denote by $V^0(p)$ the value function associated with stopping immediately at posterior p.

$$V^0(p) = \max\{-q(1-p), -(1-q)p\} \tag{1}$$

Denote by $V^1(p)$ the value associated with continuing at least one more period, and $V(p)$ the overall value function for any posterior probability p.[15] It follows that

$$V(p) = \max\left\{V^0(p), V^1(p)\right\}. \tag{2}$$

Note that $V(0) = V(1) = 0$, and therefore, $V^1(0) = V^1(1) = -k$. Furthermore, $V^1(p)$ is a convex function of p. Indeed, consider an alternative world in which with probability α, the probability that the defendant is guilty is given by p_1 and with probability $1-\alpha$, the probability that the defendant is guilty is given by p_2. If the (one) juror is not told which of the two probabilities had been realized, then she can guarantee the continuation value corresponding to $\alpha p_1 + (1-\alpha)p_2$. However, if she is told which of the two probabilities is realized, then with probability α, she can guarantee the

[13] This could be viewed as the result of a particular form of refinement. Namely, one could consider finite truncations of the game. Equilibria surviving iterated elimination of weakly dominated strategies in the agent-form game correspond to (timed) thresholds, and that sequence of thresholds converges to the thresholds we analyze here as the horizon of the game grows indefinitely.

[14] See De Groot (1970).

[15] The continuation value $V^1(p)$ is essentially the expectation of $V(p)$ with respect to the potential posteriors in the period that follows, minus the cost of an additional information unit k.

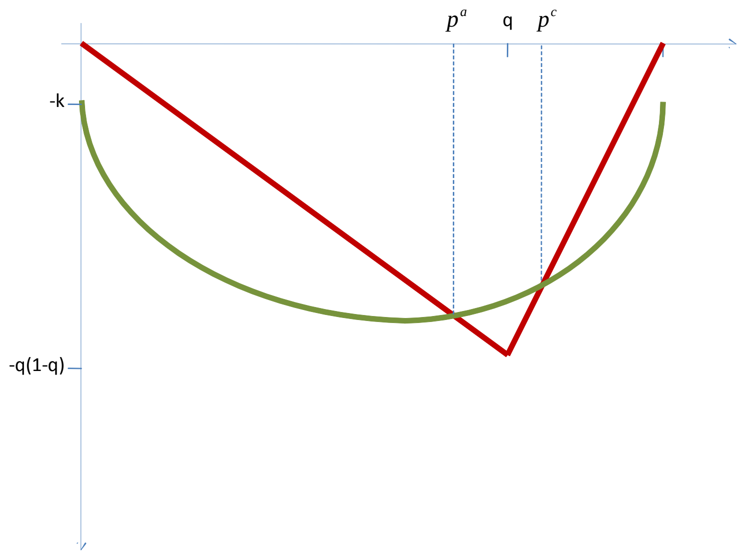

Figure 1: Homogeneous Groups – Existence and Uniqueness

continuation value of p_1 and with probability $1-\alpha$ the continuation value of p_2. Naturally, she can ignore the information provided to her, so in the latter case she must be gaining at least as much. Convexity follows. From linearity of $-(1-q)\,p$ and $-q\,(1-p)$, and the fact that their maximal value of 0 is achieved at $p=0,1$, respectively, it follows that there are two posterior probabilities (that the defendant is guilty), p^a and p^c, that define the stopping region, as in Figure 1 (see De Groot 1970, page 307).

When costs are high, they outweigh the benefits of information collection and stopping occurs immediately (in terms of Figure 1, when k is sufficiently high, the curve corresponding to the continuation payoff lies below that corresponding to the instantaneous utility from stopping). When costs are sufficiently low, there is an interior solution. Note that convexity of the value function assures the uniqueness of such an equilibrium.

For any two thresholds p^a, p^c, $p^a \leq 1/2 \leq p^c$, expected utility can be expressed as:

$$\begin{aligned} U(q;p^a,p^c) = \quad & -q\left(1-\mathbb{E}\left(p|p^c\right)\right)\Pr(p^c \text{ first} \mid p^a,p^c)- \\ & -(1-q)\,\mathbb{E}\left(p|p^a\right)\Pr(p^a \text{ first} \mid p^a,p^c) - kT(p^a,p^c), \end{aligned} \tag{3}$$

where $T(p^a, p^c)$ denotes the expected time to approach one of the posterior thresholds p^a or p^c. The expected time $T(p^a, p^c)$ is decreasing in p^a and increasing in p^c. The terms $\Pr(p^a \text{ first}|\ p^a, p^c)$ or $\Pr(p^c \text{ first}|\ p^a, p^c)$ correspond to the probabilities that the threshold p^a or p^c is reached first, respectively.[16] The expectations $\mathbb{E}\left(p|p^a\right)$ or $\mathbb{E}\left(p|p^c\right)$ denote the expected value of the posterior upon the end of deliberation conditional on passing the threshold p^a or p^c first, respectively.[17]

For presentational simplicity, we will assume that the signal distributions F_G and F_I are sufficiently well-behaved so that $\Pr(p^x \text{ first}|\ p^a, p^c)$, $\mathbb{E}\left(p|p^x\right)$, and $T(p^a, p^c)$ are twice continuously differentiable with respect to p^a and p^c, for $x = a, c$. This will allow us to use calculus techniques to identify equilibrium attributes. This assumption is satisfied for many commonly used signaling technologies. For instance, it holds if F_G and F_I are normal distributions.

We now consider a constrained problem defined by two thresholds, $\underline{p}$ and $\overline{p}$, such that the juror with preference parameter q can only choose to stop and to acquit if $p \leq \underline{p} < \frac{1}{2}$, and to stop and convict if $p \geq \overline{p} > \frac{1}{2}$. This constrained problem is helpful when constructing best responses in the problem with heterogeneous jurors. For any $\left(\underline{p}, \overline{p}\right)$, we define the constrained value functions as follows (dropping the preference q and cost k arguments, as they are apparent). As before, $V^1\left(p|\underline{p}, \overline{p}\right)$ is the value of continuing at least one period. The overall value function is given by:

$$V(p \mid \underline{p}, \overline{p}) = \begin{cases} \max\left\{V^1\left(p|\underline{p}, \overline{p}\right), -\left(1-q\right)p\right\} & p \leq \underline{p} \\ V^1\left(p|\underline{p}, \overline{p}\right) & \underline{p} < p < \overline{p} \\ \max\left\{V^1\left(p|\underline{p}, \overline{p}\right), -q\left(1-p\right)\right\} & p \geq \overline{p} \end{cases}. \tag{4}$$

The interpretation of this expression is the following: for $p \leq \underline{p}$, the juror chooses the best option between continuing deliberation and stopping to acquit. For $\underline{p} \leq p \leq \overline{p}$, the juror can only continue deliberation. For $p \geq \overline{p}$, the decision maker chooses the best option between continuing deliberation and stopping to convict.

Lemma 1 (Convexity for Constrained Problem) *The continuation value function $V^1\left(p|\underline{p}, \overline{p}\right)$ of the constrained problem is convex for $p \notin \left(\underline{p}, \overline{p}\right)$.*

Convexity of the continuation value for the constrained problem follows through similar arguments to those used for the unconstrained problem. As before, convexity implies that the solution is

[16] Note that $\Pr(p^c \text{ first}|\ p^a, p^c) = 1 - \Pr(p^a \text{ first}|\ p^a, p^c)$.

[17] Since signals are independent across time, $\mathbb{E}\left(p|p^a\right)$ does not depend on the value of p^c and $\mathbb{E}\left(p|p^c\right)$ does not depend on the value of p^a.

determined in a similar manner to that described through Figure 1 and uniqueness of the constrained solution $\left(p^a\left(\underline{p},\overline{p}\right), p^c\left(\underline{p},\overline{p}\right)\right)$ follows. The following lemma illustrates that the constrained solution is monotonic in the imposed thresholds.

Lemma 2 (Monotonicity) *$p^a\left(\underline{p},\overline{p}\right)$ is increasing in $\overline{p}$ and $p^c\left(\underline{p},\overline{p}\right)$ is increasing in $\underline{p}$.*

Monotonicity of the best responses is intuitive. Indeed, suppose one of the thresholds, say $\overline{p}$, increases. The region in which there is an effective choice between continuing information collection and halting decreases, and so the continuation value decreases. Going back to Figure 1 (that is relevant since the continuation value of the constrained problem is convex as well, as guaranteed by Lemma 1), when the continuation values decreases, the left intersection point increases. In other words, $p^a\left(\underline{p},\overline{p}\right)$ increases. Similar arguments hold for changes in $\underline{p}$.

We now turn to some properties of the homogenous jury's deliberation process that prove useful subsequently.

In homogeneous committees, agents agree on what should be done both during deliberation as well as during the final decision making stage. Therefore, from an institutional perspective, the interesting parameters to inspect are the preference parameter q and the cost of deliberation k. The following proposition summarizes the effects of changes in these two parameters.

Proposition 2 (Homogeneous Juries – Comparative Statics)

1. **Preference Parameter q.** *$p^a(q;k), p^c(q;k)$ weakly increase in q.*

2. **Cost** k. *$p^a(q;k)$ weakly increases in k, $p^c(q;k)$ weakly decreases in k. Consequently, the time to take a decision is decreasing in k.*

Intuitively, as q increases, agents care more about convicting the innocent relative to acquitting the guilty. It follows that they are willing to spend more time preventing the former relative to the latter, and that the range of posteriors for which the jury acquits becomes larger (similarly, the range of posteriors for which the jury convicts becomes smaller). When the cost k increases, less information is gathered (implying that the posterior thresholds shift toward the prior) and therefore deliberation takes less time.

An immediate consequence of Proposition 2 and Lemma 2 is the following (recalling that best responses in the constrained problem depend on the underlying preference parameter and information cost, which we do not spell out for readability's sake):

Corollary 1 (Comparative Statics of Constrained Problem *For any fixed* $(\underline{p}, \overline{p})$, $p^a(\underline{p}, \overline{p})$ *and* $p^c(\underline{p}, \overline{p})$ *weakly increase in* q.

4. Heterogenous Preferences

We now shift our attention to juries composed of agents with potentially heterogeneous preferences. Namely, we assume $q_1 \leq q_2 \leq ... \leq q_n$ and allow for some of the inequalities to be strict. In order to isolate the effects of preference heterogeneity on outcomes, we assume in this section that deliberation costs are homogenous and fixed at $k > 0$.[18]

Throughout our discussion, we select the sincere voting equilibrium at the decision stage, the one entailing strategies that are not weakly dominated. That is, when deliberation stops at time t with a posterior probability of guilt of p_t, agent i votes to convict if and only if $p_t \geq q_i$.[19]

We start by considering the case in which voting rules in the deliberation and decision stage coincide. That is, $R_d = R_v$. This will allow us to focus on one set of pivotal agents, rather than consider pivotal agents at each stage of the decision-making process. Later, we inspect the impacts of discordance between the two types of rules.

Lemma 3 implies that the pivotal agent for stopping when $p_t < 1/2$ is juror R_d and the pivotal agent when $p_t > 1/2$ is juror $n - R_d + 1$. In order to make the comparison with the results pertaining to homogeneous committees transparent, we focus on equilibria that are characterized by stationary thresholds. The following Lemma will be useful throughout our analysis:

Lemma 3 (Reduction to Two Juror Juries) *When* $R_d = R_v$, *any equilibrium thresholds corresponding to a jury composed of jurors with preference parameters* $q_1 \leq q_2 \leq ... \leq q_n$ *are also equilibrium thresholds of a jury composed of two jurors with preference parameters* q_{n-R_d+1}, q_{R_d} *in which both deliberation and decision rules are unanimous.*

Lemma 3 says that equilibrium thresholds can be identified through the preferences of two jurors. Intuitively, when posterior probabilities of guilt are low, it is the jurors who care most about the

[18] We return to the case of heterogeneous costs in Section 9.2.

[19] We assume the juror convicts upon indifference ($p_t = q_i$). This tie breaking rule is of no important consequence in our analysis as it pertains to zero probability events.

mistake of convicting the innocent that determine the decision. Note that whenever agent j prefers to continue deliberation, so does any agent $l > j$ who worries even more about innocent convictions. In particular, whenever juror $j = R_d$ chooses to continue deliberation, or vote to convict, so will all jurors $l > R_d$, and deliberation will carry on. Similarly, whenever posterior probabilities of guilt are high, it is the jurors who worry most about guilty acquittals that determine decisions, the relevant pivotal juror being juror $n - R_d + 1$.

Importantly, the lemma suggests that equilibrium outcomes need not necessarily be efficient and depend crucially on the preference distribution of jurors other than the pivotal ones. For instance, when unanimity is imposed at the deliberation stage, inefficiencies can arise when there are very many agents of preference $q_j < \frac{1}{2}$, while $q_1 + q_n > 1$.

Best responses of the pivotal agents can be derived through (4). Each of the agents takes one of the thresholds as given and optimally chooses the other one (that corresponds to the region she cares more about). In what follows we denote by p_* the lower equilibrium threshold and by p^* the upper equilibrium threshold. Lemma 3 implies that $p_* = p^a\left(p_*, p^*; q_{n-R_d+1}\right)$, and $p^* = p^c\left(p_*, p^*; q_{R_d}\right)$.[20]

In what follows, we move away from the assumption that $R_d = R_v$ and inspect the consequences of different deliberation and decision rules in general juries.

5. Arbitrary Deliberation and Voting Rules

We now consider a jury composed of n jurors of arbitrary preferences $q_1 \leq q_2 \leq ... \leq q_n$ and contemplate differing constellations of voting rules. When $R_d \neq R_v$, there are two sets of relevant pivotal agents: those pertaining to the deliberation stage and those pertaining to the decision stage.

In analogy to Lemma 3, during the decision stage, whenever juror j would prefer to convict if she were dictator, so would any juror $l < j$. Whenever juror j would prefer to acquit if she were dictator, so would any juror $l > j$. It follows that the jurors to focus on are those pivotal during deliberation: jurors R_d and $n - R_d + 1$, and those pivotal during the decision stage: jurors R_v and $n - R_v + 1$.

We first analyze environments in which deliberation costs are low. In such cases, equilibrium behavior will entail a high volume of information collection. This would suggest that in equilibrium, when information collection ends, agents would be at a consensus on what should be done. Formally,

[20] In order to stress the dependence on individual preferences, we use the matural notation $p^a(\underline{p}, \bar{p}; q)$ and $p^c(\underline{p}, \bar{p}; q)$ to denote the constrained solution for the agent of taste parameter q.

Lemma 4 (Low Costs – Convergence of Opinions) Consider a jury $q_1, ..., q_n$. *For any* R_v *and* R_d, *and any* $p_1 < p_2 \in (0,1)$, *there is a sufficiently low deliberation cost* $\widehat{k}$ *such that, for* $k < \widehat{k}$, *equilibrium thresholds* (p_*, p^*) *are such that* $p_* < p_1$ *and* $p^* > p_2$.

Lemma 4 implies that any set of jurors would agree on the decision ex-post when costs are sufficiently low even if unanimity is not a requirement for making decisions.[21]

Suppose the most extreme jurors care about both types of mistakes, $q_1, q_n \in (0,1)$, and set $\tilde{q}_1 = q_1$ and $\tilde{q}_2 = q_n$. The lemma suggests that for sufficiently low deliberation costs, if $q_1 > 1/2$ or $q_n < 1/2$, if deliberation were not possible, agents would agree at the outset on the optimal action. In the presence of deliberation, however, since there is positive probability that at some point $t > 0$, $p_t \in (q_1, q_n)$, agents can disagree on the optimal action to take during the deliberation process. This is consistent with some of the empirical research on jury deliberation processes. For example, Hannaford, Hans, Mott, and Musterman (2000) documented frequent opinion changes during deliberations in the 1995 Arizona trials.

The lemma also implies that for sufficiently low costs, deliberation will render the jury in consensus on what should be done. In particular, the voting rule R_v in the decision stage would not matter, and only the deliberation rule drives the length of the deliberation process.

Another case in which the voting rule R_v does not affect outcomes is when it entails a less demanding majority requirement than the deliberation rule. In that case, whenever deliberation takes place, when there is a sufficient majority to halt deliberation, there will be a corresponding majority to acquit or convict the defendant in the decision stage. In fact, whenever the deliberation rule is more demanding than the decision voting rule ($R_d \geq R_v$), even when costs are not necessarily low, if agents R_d and $n - R_d + 1$ follow the strategies they would had they been the only jurors and both deliberation and decision rules were unanimous, they achieve identical outcomes to those with rules R_d and R_v. In particular, the set of equilibrium outcomes does not depend on R_v.

The following proposition summarizes our discussion of the two cases in which the decision rule has no effect on final outcomes.

[21] This result relies on the fact that jurors care about both types of mistakes: convicting the innocent and acquitting the guilty, so that $\tilde{q}_1, \tilde{q}_2 \neq 0, 1$. Naturally, as $\tilde{q}_1$ approaches 0 or $\tilde{q}_2$ approaches 1, the costs assuring ex-post concensus approach 0.

Proposition 4 (Decision Rule Irrelevance) *For any deliberation rule R_d,*

1. *(Restricted Irrelevance) For any decision voting rules R_v, $\tilde{R}_v \leq R_d$, the set of equilibrium outcomes corresponding to R_v and $\tilde{R}_v$ coincide.*

2. *(Irrelevance due to unanimous agreement: low costs) For any given preference profile, there exists a $\underline{k}$ such that, for $k \leq \underline{k}$, the voting rule at the decision stage R_v is irrelevant for equilibrium outcomes. In particular, time to decision or probability of mistakes do not depend on R_v.*

Proposition 4 outlines two important cases in which the voting rules at the decision stage do not matter. There are, however, cases in which the voting rule at the decision stage are important for outcomes. Consider a case in which $R_v > R_d$ and relatively high cost of deliberation k. Had the pivotal jurors at the deliberation stage (agents $n - R_d + 1$ and R_d) ignored the fact that more extreme jurors (agents $n - R_v + 1$ and R_v) are pivotal at the decision stage, there would potentially be disagreement in the decision stage and the jury would end up as hung. Thus, in these cases, the pivotal jurors at the deliberation stage face a trade-off: they can either prolong deliberation to convince the pivotal jurors in the decision stage, or they can halt deliberations immediately. If the costs of deliberation are not too high, some additional deliberation may therefore be beneficial. Intuitively then, in these cases one should expect that a unanimity voting rule at the decision stage will lead to longer deliberation and more accurate decisions than simple majority. We show below that this is true for juries with symmetric preferences (around 1/2). When juries are asymmetric, changing the decision rule or the deliberation rule may not lead to uniformly more accurate decisions because, for instance, more accurate acquittal decisions may come hand in hand with less accurate conviction decisions: it can be the case that, say, making the decision rule more extreme reduces the acquittal equilibrium threshold p_* but also reduces the equilibrium conviction threshold p^*.

6. Symmetric Juries

For simplicity, we first go back to the case $R_d = R_v$. Lemma 3 allows us to restrict attention to two jurors within the jury: $\tilde{q}_1 = q_{n-R_d+1}$ and $\tilde{q}_2 = q_{R_d}$. Assuming $\tilde{q}_1$ and $\tilde{q}_2$ are symmetric around $\frac{1}{2}$, i.e., $\tilde{q}_1 = \frac{1}{2} - \delta$ and $\tilde{q}_2 = \frac{1}{2} + \delta$ for some $\delta \in \left[\frac{1}{2}, 1\right]$, simplifies equilibrium characterization significantly.

Definition (Symmetry in Juries) *We say the jury is quasi-symmetric with respect to $R_d = R_v$ whenever $q_{n-R_d+1}+q_{R_d} = 1$ and information is symmetric, i.e., for any $s \geq 0$, $F_G(s) = F_I(-s)$. A jury is* symmetric *whenever it is quasi-symmetric with respect to all voting rules.*

When juries are quasi-symmetric, we focus on *symmetric threshold equilibria* corresponding to the relevant deliberation rule, ones in which both posterior thresholds are symmetric around 1/2 (i.e., equally distanced from 1/2). As it turns out, quasi-symmetric juries generate unique predictions, established in the following lemma.

Lemma 5 (Quasi-symmetric Juries - Uniqueness) *Assume the jury is quasi-symmetric with respect to R_d. Then, for sufficiently low costs, there exists a unique stationary symmetric and non-trivial threshold equilibrium when the deliberation rule is R_d.*[22]

Lemma 5 implies that when the jury is symmetric and costs are sufficiently low, symmetric equilibrium thresholds are determined uniquely for any voting rule. The lemma is a direct consequence of the monotonicity implied by Lemma 2. Indeed, if there were two threshold equilibria, the ranking of the left thresholds must coincide with the ranking of the right thresholds. Therefore, it is impossible for two such equilibria to both be symmetric.

We start our analysis with juries that are quasi-symmetric with pivotal jurors as above, $\tilde{q}_1 = \frac{1}{2} - \delta$ and $\tilde{q}_2 = \frac{1}{2} + \delta$ for some $\delta \in \left[0, \frac{1}{2}\right]$. This will allow us to identify the impacts of diversity in the jury, as captured by the spread δ, and open the door for inspecting the effects of the voting rules, which determine how moderate or extreme the pivotal jurors are.

Denote the resulting symmetric equilibrium thresholds by $p_*(\delta) \leq 1/2 \leq p^*(\delta)$ (where we drop the cost and voting rule arguments for ease of presentation). Symmetry entails $p_*(\delta) + p^*(\delta) = 1$.

As δ increases, the juror with preferences $\tilde{q}_1$ is increasingly concerned about acquitting the guilty, while the juror with preferences $\tilde{q}_2$ is increasingly concerned about convicting the innocent. There are now two forces at play. The direct one is that the first agent would like to spend more time collecting information when the posterior is lower than 1/2, while the second agent would like to spend more time collecting information when the posterior is greater than 1/2. Indeed, this follows from the first part of Proposition 2, implying that $p^a(\tilde{q}_1) \leq p^a(\frac{1}{2}) \leq p^a(\tilde{q}_2) \leq 1/2 \leq p^c(\tilde{q}_1) \leq p^c(\frac{1}{2}) \leq p^c(\tilde{q}_2)$.

[22] A symmetric threshold equilibrium is one in which both posterior thresholds are symmetric around 1/2 (equivalently, equally distanced from 1/2). We call the threshold equilibrium non-trivial if it entails some amount of information collection.

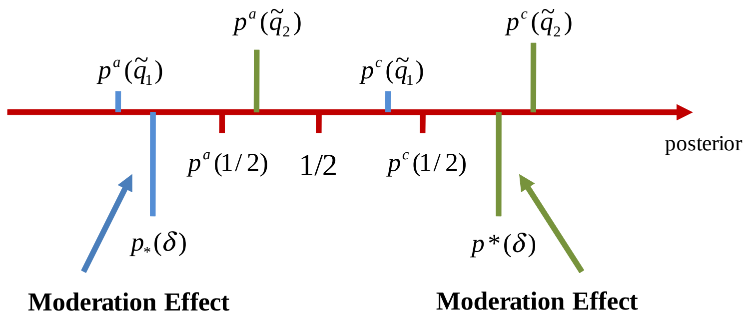

Figure 2: Equilibrium Spread and the Moderation Effect in Quasi-symmetric Juries

The indirect effect comes from the strategic interaction. Consider, say, the first juror and the event in which the posterior $p_t \in (p^a(\tilde{q}_1), p^a(\tilde{q}_2))$, so that if she were by herself she would continue collecting information, while the other juror by herself would not. Importantly, the continuation value for pursuing information collection is now different than that corresponding to the case in which juror 1 is the solo juror. Indeed, juror 1 may suspect that when $p_t > 1/2$, juror 2 will push for prolonging deliberation, even when she herself is ready to make a decision (in the analogous range $p_t \in (p^c(\tilde{q}_1), p^c(\tilde{q}_2)))$. Thus, continuation values are lower, suggesting that the resulting equilibrium thresholds are moderate relative to the most extreme individual thresholds $p^a(\tilde{q}_1), p^c(\tilde{q}_2)$, as depicted in Figure 2 and formalized in the following proposition.

Proposition 5 (Equilibrium Spread and Moderation)

1. *(Spread)* $p_*(\delta)$ *is decreasing in* δ*,* $p^*(\delta)$ *is increasing in* δ*. In particular, the time it takes for a decision is increasing in* δ*.*

2. *(Moderation Effect) For any* $q = \frac{1}{2} + \delta$*, where* $\delta \in \left(0, \frac{1}{2}\right)$*,* $p_*(\delta) = 1 - p^*(\delta) \leq p^a(q)$ *and* $p^*(\delta) \leq p^c(q)$*. Furthermore, for sufficiently small information costs* k*, these inequalities are strict.*

The proposition implies that increased heterogeneity in the jury (manifested in a higher δ) will reduce the two types of mistakes, and increase the expected time to a decision. This is consistent with the empirical observations of Sommers (2006), who used a mock jury paradigm to test for the effects of racial heterogeneity on jury performance and found that heterogeneity was associated with longer deliberation and more accurate decisions. In a similar vein, Goeree and Yariv (2010) found increased preference heterogeneity to be associated with longer deliberation times in the laboratory.

The spread of symmetric pivotal agents can be manipulated through the voting rule. Indeed, the more demanding the deliberation rule (a higher $R_d = R_v$), the greater the spread. Formally, note that $q_{R_d} - q_{n-R_d+1}$ is increasing in R_d. Using part 1 of Proposition 5, we therefore get the following corollary.

Corollary 2 (Accuracy and Deliberation Rules) *In symmetric juries, deliberation length and accuracy of decisions increase with the deliberation and voting rules $R_d = R_v$.*

So far, our discussion has focused on deliberation and decision rules that coincide. Recall that Proposition 4 posed the irrelevance of the decision rules when either the deliberation rule is more demanding than the decision rules under consideration or information costs are sufficiently low. When juries are symmetric, we can discuss the effects of decision rules more generally, even while the conditions for the irrelevance highlighted in Proposition 4 do not hold.

As it turns out, when the decision rule R_v is more demanding than the deliberation rule R_d, $R_v \geq R_d$, non-trivial symmetric equilibrium thresholds are still determined uniquely. Essentially, there are two cases to consider. First, when costs of deliberation are low, the equilibrium deliberation thresholds are sufficiently wide that the super-majority requirement at the decision stage is automatically met and exceeded. In the second case, with higher costs and $R_v > R_d$, the pivotal jurors at the deliberation stage would like to settle for deliberation thresholds $p_* > q_{n-R_v+1}, p^* < q_{R_v}$. However, such thresholds would lead to a hung jury. In this scenario, the equilibrium deliberation thresholds are driven by the requirement to reach sufficient consensus at the decision stage so we obtain $p_* = q_{n-R_v+1}, p^* = q_{R_v}$: deliberation continues just until the moment the pivotal jurors at the decision stage are persuaded to join the required consensus.[23]

[23] When costs are sufficiently high, achieving a concensus at the decision stage becomes too costly for the pivotal jurors at the deliberation stage and the unique equilbrium outcome is that of no information collection and an immediate hung jury.

In the following proposition, we denote by $(p_*(R_d, R_v; k), p^*(R_d, R_v; k))$ the unique symmetric equilibrium thresholds corresponding to deliberation rule R_d and decision rule $R_v \geq R_d$.

Proposition 6 (Decision Rule Relevance: Inclusiveness Effect) *Consider a symmetric jury. For any deliberation rule R_d, take two voting rules $\tilde{R}_v > R_v \geq R_d$.*

1. *There exist $\underline{k}, \overline{k}$ such that, for $\underline{k} < k < \overline{k}$, corresponding symmetric equilibrium thresholds satisfy $p_*\left(R_d, \tilde{R}_v; k\right) < p_*(R_d, R_v; k)$ and $p^*\left(R_d, \tilde{R}_v; k\right) > p^*(R_d, R_v; k)$: the larger the supermajority required for making a decision, the more information collection there is; the deliberation time and decision accuracy are greater under voting rule $\tilde{R}_v$ than under voting rule R_v.*

2. *There exist $\overline{k}$ such that, for $k < \overline{k}$, deliberation time and accuracy would be even greater under deliberation rule $\widetilde{R}_d = \tilde{R}_v$: $p_*\left(\tilde{R}_d, \tilde{R}_v; k\right) < p_*\left(R_d, \tilde{R}_v; k\right)$* and *$p^*\left(\tilde{R}_d, \tilde{R}_v; k\right) > p^*\left(R_d, \tilde{R}_v; k\right)$.*

Part 1 of Proposition 6 is in contrast with the results in Feddersen and Pesendorfer (1998), Persico (2004), and Austen-Smith and Feddersen (2006). The intuition for this result can be understood by considering a special case. Consider a jury where R_d is simple majority. We contemplate the effect of moving from R_v = simple majority to R_v = unanimity. Suppose that costs of deliberation are sufficiently high that when R_v is simple majority, it is not worthwhile for the median juror to deliberate long enough to reach consensus on the decision. Then, under unanimity, the median juror who is still pivotal in the deliberation process understands that, in order to reach a verdict, he cannot stop deliberation as early as when R_v = simple majority. In order to avoid a hung jury he must convince the the extreme juror to vote with with everyone else. This requires longer deliberation. When costs are not too high, it is worth it to deliberate just long enough to obtain these jurors' votes on the decision.

Continuing the same example, Part 2 of Proposition 6 says that moving to R_d = unanimity would lead to even longer deliberation. The reason is that the most extreme voters are now in a position to directly affect the deliberation decision, and they desire longer deliberation than the median juror.

Taken together with Proposition 4, Part 2 of Proposition 6 suggests that deliberation rules are more powerful than decision rules in affecting the process of jury decision making and deliberation, the resulting deliberation time and decision accuracy in particular.

These results imply that, in essence, interior equilibria *always* depend only on two jurors. When $R_v \leq R_d$, the jury outcome is equivalent to that of a jury composed of two jurors with preferences q_{R_d} and q_{n-R_d+1} (and unanimous deliberation and voting rules), while when $R_v > R_d$, any jury outcome entailing non-trivial deliberation is equivalent to that of a jury composed of two jurors with preferences q_{R_v} and q_{n-R_v+1} (and, again, unanimous deliberation and voting rules).

In practice, it may be the case that a change in the decision voting rule is tied to a change in the deliberation rule, a so-called *protocol effect*. In the presence of such a protocol effect, the decision voting rule has a clear impact. Indeed, when the voting and decision rules coincide, Lemma 3 holds, so that two pivotal jurors determine outcome. The more demanding the decision voting rule, the more extreme these two jurors are. Consequently, more stringent decision voting rules would correspond to longer deliberation and more accurate decisions.

7. Welfare and Delegation

Welfare effects are difficult to assess as they depend on the perspective from which welfare is calculated (in terms of the distribution of preference parameters in the relevant population and the extent to which time costs are internalized).

First consider a homogeneous jury. From the point of view of the agents, deliberation is weakly beneficial. Indeed, the jury can always choose not to deliberate by fixing the prior 1/2, $p^a = p^c = 1/2$. From an institutional point of view, when deliberating groups are homogeneous, a designer (say, the constitution writers) characterized by preference parameter q who internalizes the costs (e.g., when these costs are linked to the time spent on making decisions and not engaging in other profitable activities) is best off with a committee (jury) comprised of identical agents of preference parameter q as well. In fact, a committee composed of more extreme agents than the designer would entail "too much" information collection. The designer may then benefit by increasing the costs of the committee members, or putting a cap on deliberation time.

From the perspective of the participating jurors, in any quasi-symmetric jury, we can assess the optimal spread of the pivotal agents. It turns out that little spread is most preferred, as captured by the following proposition.

Proposition 7 (Optimal Delegation) *Jurors have unanimous preferences over deliberation rules: all jurors in a quasi-symmetric jury prefer pivotal agents with as little spread as possible or* $R_d = \lceil n/2 \rceil$.

Intuitively, recall expression (3) for a juror's utility. In a quasi-symmetric jury, thresholds are symmetric, and therefore, the first two terms in (3) are a convex combination (via q_i) of an identical expected probability of mistake. It follows that the expected utility does not explicitly depend on q_i. In particular, all of the jurors gain the same level of expected utility as would a juror with preference parameter $\frac{1}{2}$ if she were to have the equilibrium thresholds imposed upon her. However, note that a juror with preference parameter $\frac{1}{2}$ would prefer no spread at all ($\delta = 0$ in our notation above), as then she receives her optimal thresholds. Monotonicity then implies our result.[24]

Proposition 7 is particularly stark because of symmetry. However, the effect highlighted in this proposition is more general: even in a large class of asymmetric juries, the most extreme jurors will not push for unanimity at the deliberation stage because unanimity means that deliberation is long on *both* sides, making the cost of deliberation too high from an ex-ante perspective to make it worth reducing the probability of mistakes further.

It is also useful to point to a contrast between decision rules and deliberation rules at this point. Proposition 7 provides a rationale for the fact that, while deliberation may take place with minimal majority rules, or equivalently under the control of a moderate chairman (with $q = 1/2$), decisions may require supermajorities. Indeed, it is obvious that no juror would willingly consider a decision rule that would end up excluding her.

8. Simultaneous Deliberation

We now discuss a case in which the decision on the amount of information to be collected takes place in one shot and contrast this case with the sequential one considered up to now. When jurors are homogeneous, this is equivalent to the classic case of choosing the optimal sample size for the test of a binary hypothesis (see De Groot 1970). In our version with heterogeneous jurors we need to specify some details of the model. A deliberation decision determines the sample size t. A sample of size t costs each juror kt. At time t, jurors observe the realization of the sequence of random variables $X_1, ..., X_t$, and the vote whether to acquit or convict according to a decision rule R_v just as in Section 2. Deliberation is determined as follows. All voting takes place before the sample is drawn according to deliberation rule R_d. An index moves over discrete time starting from 1. At index τ, if jurors have not yet come to an agreement, then jurors vote on whether sample size τ is

[24] Proposition 7 hints at the possible effectiveness of deliberation taxes. Indeed, increasing the costs of deliberation would lead to shorter deliberation times which may be preferrable to at least a fraction of the population.

acceptable. If at least R_d jurors agree that the sample size is sufficient, then the deliberation process is over and a sample of size τ is drawn. If fewer than R_d jurors agree, then the index moves on to $\tau + 1$. The process continues until an R_d majority is satisfied. This model would be identical to our sequential deliberation model if voters had to stop deliberation without seeing the realizations of the random variables. Given our result below that deliberation is always unanimous, the exact deliberating protocol is irrelevant. However, the model described above is easier to work with and is a closer match to the sequential deliberation model.[25]

Let p_t be the posterior if the deliberation process has yielded a sample size t. Then, at date t, a juror of type q votes to convict if $p_t \geq q$, and votes to acquit if $p_t < q$. If at least R_v votes are obtained, then a decision is reached. Otherwise we have a hung jury. Let $U(H)$ be the payoff to all jurors when there is a hung jury. We assume that $U(H)$ is independent of q.[26]

Proposition 8 (Simultaneous Deliberation: Voting Rule Relevance) *In a symmetric jury, under simultaneous deliberation, jurors have common preferences over deliberation decisions. Therefore, the deliberation rule R_d is irrelevant. However, the voting rule matters: if $\widetilde{R}_v > R_v$, a jury voting under voting rule $\widetilde{R}_v$ chooses to collect more information.*

The intuition for the irrelevance of the deliberation rule is related to the intuition of Proposition 7. Given that deliberation is simultaneous, jurors evaluate the optimal amount of information to be collected ex-ante, before seeing the realization of any signals. All jurors simply trade off increased accuracy against the cost of information collection independent of their preference parameters because increased information collection reduces mistakes of both types equally.

The intuition for the effect of the voting rule is the following. Under simultaneous deliberation, for any given amount of gathered information, a larger voting rule raises the probability of a hung jury. Acquiring additional information reduces the probability of this costly event.

This result is in sharp contrast with the results we obtained for the case of sequential deliberation. This is not very surprising given the very different nature of deliberation in the two scenarios.

[25] As in the previous analysis, there are possible multiple equilibria. As before, we can think of a refinement where one considers finite truncations of the game. Equilibria surviving iterated elimination of weakly dominated strategies in the agent-form game would correspond to (timed) thresholds, and that sequence of thresholds converges to the thresholds we analyze here as the horizon of the game grows indefinitely.

[26] This will hold, for instance, if in the event of a hung jury, the defendant is acquited or convicted with equal probability. Of course, a fixed cost of a hung jury independent of q is also compatible with this assumption.

The contrast between the consequences of simultaneous as opposed to sequential protocols is also familiar from the literature on search and auctions. Note also that, in contrast with the case of sequential deliberation, even with symmetry, the simultaneous scenario allows for the coexistence of significant information collection and hung juries. However, even in the simultaneous scenario, hung juries are less likely with longer deliberation.

There are a number of interesting additional comparisons that can be made between the sequential and simultaneous scenarios. First, there is a strong general effect leading to welfare being higher under sequential deliberation: welfare is obviously unambiguously higher in the sequential case for the case of a single juror because more efficient use of information is made. Indeed, this was the original motivation behind Wald's analysis. By Proposition 7 we can also conclude that welfare from the point of view of the committee is higher in the sequential case under simple majority when juries are symmetric.

Another interesting comparison concerns the likelihood of consensual votes. For low costs, sequential deliberation leads to unanimous verdicts regardless of the decision rule (see Proposition 4). In contrast, simultaneous deliberation generates a positive probability of some disagreement for any voting rule, for any costs, because there are always positive probability histories of signals that are not very informative. For intermediate costs the comparison is less straightforward, but, for any fixed voting rule, simultaneous deliberation tends to generate more variation in consensus because in the case of sequential deliberation the vote is more likely to end at a quorum.[27]

9. Discussion and Extensions

9.1. Random Juries. In our model, jurors' preferences are given. A natural extension would allow some randomness in the preferences of the selected jurors.[28] Suppose that, at the outset, the opposing lawyers and the judge select a jury composed of individuals with preferences drawn independently from a distribution G over $[0,1]$. For simplicity, assume that: 1. The population is ex-ante symmetric, so that $G(x) = 1 - G(1-x)$, and 2. Jurors, once selected, are transparent about

[27] In order to see this, it is useful to consider a continuous time, continuous signal version of the model. In such a version, deliberation always stops exactly at the threshold of the pivotal jurors.

[28] In some cases, the process of voir dire in commonwealth countries as well as the U.S. effectively restricts preference profiles of juries. Nonetheless, the process cannot pick out fully the characteristics of jurors and so some randomness remains. This is true for many other collective decision processes in which the agenda is set for several generations of agents, so that rules are not tailored to a particular familiar committee.

their preferences, so that they are common knowledge.[29]

In order to illustrate the effects of such randomness on outcomes and welfare, consider the case in which $R_d = R_v$, so that Lemma 3 holds. It follows that the relevant preferences to consider are the R_d'th and $n - R_d + 1$'th *order statistics* of the sampled jury preference profile. In particular, if we compare two populations, characterized by distributions G and G', with one more variant than the other, so that G' is a mean preserving spread of G, the expected order statistics will be more extreme under G' than under G.

Even though Lemma 3 holds and, for any selected jury, it is only two jurors who effectively determine outcomes, the size of the jury now plays an important role as well since it affects the variance of the preferences of these two pivotal jurors. In that respect, it would be important to understand the curvature of the (constrained) best-response thresholds. This would be especially important if one considered agenda setters that experienced some level of risk aversion (which, in our baseline model, plays no role). In such settings, it is the interplay between the size of the jury and the voting rule that determine the distribution of outcomes.

For sufficiently large n, juries will be approximately symmetric. Therefore, using the results of Proposition 5, we make two conjectures. First, more stringent voting and deliberation rules will generate more extreme pivotal jurors and therefore lead to greater expected times to decisions and smaller expected probabilities of mistakes. Similarly, fixing the voting rule and contemplating a distribution G' that is a mean preserving spread of G, would yield more extreme pivotal jurors and analogous effects on timing and accuracy outcomes.

9.2. Heterogeneous Deliberation Costs. Suppose now that jurors differ in the costs that are imposed upon them through deliberation (e.g., if costs are linked with the time away from work, variance in wages may translate to variance in deliberation costs). Formally, in order to assess the effects of cost heterogeneity, we assume that all jurors share the same preference parameter q, but juror i's deliberation cost is given by k_i, where without loss of generality $k_1 \geq k_2 \geq ... \geq k_n$.

Note that the decision rule R_v does not affect outcomes since for any given posterior the jurors all agree on the optimal action to be taken. The voting rule, however, does have an effect. Whenever

[29]We can think of the institutional designers as the constitution writers, who put agendas in place having only a distribution of cases and juries in mind. Introducting incomplete information into the model we analyze through preferences would be interesting, though beyond the scope of this paper. In such a setup, behavior during the deliberation phase could serve to signal agents' preferences.

agent j wants to stop information collection, so does any agent experiencing higher costs ($l < j$). It follows that the pivotal juror during deliberation is the R_d'th juror. Consequently, we get the following.

Proposition 9 (Heterogeneous Costs) *A jury with rule R_d chooses thresholds of a homogeneous committee with costs k_{R_d} . Hence, deliberation length and accuracy of decisions increase with the decision rule R_d.*

Proposition 9 implies that a designer who does not internalize the jury's deliberation costs would be inclined to choose as demanding a deliberation rule as possible. The welfare optimal deliberation rule, however, depends on the distribution of waiting costs in the relevant population.

9.3. Civil Juries. We now consider an example of a related model where a jury must take a decision from a continuum of possible choices. This can be interpreted as a model of a civil jury choosing the amount of damages to award a plaintiff. The jury is uncertain about the true level of damages D. The prior distribution over these true damages is given by a normal distribution $N(\mu, \frac{1}{p_0})$ with mean μ and precision p_0.

Suppose we allow a limited degree of heterogeneity among jurors as above that is given by how costly it is for them to continue collecting information (in the current setting, this will be tantamount to allowing heterogeneity in how strongly each juror desires to make the correct decision). Specifically, assume the payoffs for each juror if true damages are D and the jury awards Q are given by

$$U(D, Q) = -\alpha(D - Q)^2,$$

where $\alpha > 0$.

The jury deliberates as in the model presented in Section 2: at each deliberation date they observe a new signal X_t at cost k. The sequence $X_1, X_2, ...$ is conditionally i.i.d., normal with mean D and precision p_X: $N(D, \frac{1}{p_X})$. The jury stops deliberating if at least R_d jurors vote to stop, otherwise it continues. Note that, given the assumption about payoffs, once deliberation has ended, the jury is unanimous about the optimal decision. Thus, all disagreements arise in deliberation choices.

The optimal choice if the jury stops deliberating at t is the conditional expectation of D (equivalently, X_{t+1}) given the prior history. As is well known, in this normal quadratic setting, this conditional expectation takes a convenient form:

$$\mathbb{E}[X_{t+1}|X_1 = x_1, \ldots, X_t = x_t] = \frac{p_0\mu + p_X \sum_{s=1}^{t} x_s}{p_0 + tp_X}.$$

Thus, the payoff to a juror experiencing a cost k when the jury stops at time t is given by

$$-\frac{\alpha}{p_t} - kt = -\frac{\alpha}{p_0 + tp_X} - kt \tag{5}$$

Note that this payoff is independent of the realizations of $X_1, ...X_t$ so, in this setting, in contrast with our prior analysis, there is no difference between sequential and simultaneous deliberation.

From equation (5) we can immediately conclude that jurors with lower costs k want to stop later and we obtain a similar result to our previous analysis concerning the effects of deliberation rules:

Proposition 10 (Deliberation in Civil Juries) *The accuracy of damage awards is higher under more stringent deliberation rules.*

Note that, in equation (5), a increasing the cost k has similar effects to lowering the preference parameter α. In particular, as mentioned above, cost heterogeneity plays a similar role to preference heterogeneity (when manifested through heterogeneous parameters α in the jury).

9.4. Incomplete Information, Stationarity, and Hung Juries. Throughout the paper, we have assumed that jurors' preferences are commonly known. This assumption allowed us to focus on stationary strategies and extract the main tensions between the deliberation and decision phases. Nonetheless, a natural extension to our model is to the case in which jurors have some incomplete information about the learning process at hand, either due to preferences that are not commonly known or due to the informativeness of the collective signals not being fully transparent. In such environments, the process of deliberation confounds two learning processes: regarding the guilt of the defendant, and regarding the prevailing characteristics of the jury (distribution of preferences or signal informativeness). In particular, the deliberation phase is inherently non-stationary.

While the analysis of such a model requires some novel techniques and goes beyond the scope of the current paper, we view it as especially important for explaining the patterns identified by the empirical literature regarding hung juries. Indeed, in such a model, it is conceivable that the longer deliberation goes on, the more likely it is that jurors are "high strung" or that the process is not very informative, and that agreement is likely to take a longer time than was initially estimated. Under certain additional conditions, this modification is likely to deliver that hung juries deliberate longer.[30] This would be in line with the evidence provided by Kalven and Zeisel (1966) and Hans (2003), who find that hung juries deliberate a significantly longer time than juries that deliver a verdict.[31] Furthermore, the tensions between costly information collection and decision accuracy, that are the driving force of our results, would persist in such a setting.

[30] An alternative assumption that we suspect would lead to a similar conclusion is that deliberation costs are increasing in time.

[31] In our baseline setting of complete information, a robust consequence is that even in cases of asymmetries, hung juries deliberate for a shorter time than juries that deliver a verdict. The reason is that agents can anticipate when a hung jury is likely to occur and thereby not invest in any information collection whatsoever.

10. Appendix

Proof of Lemma 1

Consider $p_1, p_2 \leq \underline{p}$. For both p_1 and p_2 the decision maker can choose to stop. In this case, $V^1\left(\alpha p_1 + (1-\alpha)\, p_2 \mid \underline{p}, \overline{p}\right) \leq \alpha V^1\left(p_1 \mid \underline{p}, \overline{p}\right) + (1-\alpha)\, V^1\left(p_2 \mid \underline{p}, \overline{p}\right)$ follows from the same argument as in the unconstrained case. Namely, consider an alternative world in which with probability α, the posterior probability that the defendant is guilty in the period that follows is given by p_1 and with probability $1-\alpha$, that probability is given by p_2. If the agent is not told which of the two posteriors had been realized, she can guarantee the continuation value corresponding to $\alpha p_1 + (1-\alpha)\, p_2$. However, if she is told which of the two probabilities is realized, then with probability α, she can guarantee the continuation value of p_1 and with probability $1-\alpha$ the continuation value of p_2. Since she can always ignore the information provided to her, in the latter case she must be gaining at least as much and convexity follows. Similar arguments follow for $p_1, p_2 \geq \overline{p}$. ■

Proof of Lemma 2

For any $p, \underline{p}, \overline{p}$,

$$\max\left\{V^1(p \mid \underline{p}, \overline{p}), -q\,(1-p)\right\} \geq V^1(p \mid \underline{p}, \overline{p}).$$

Consider $\overline{p}_1 > \overline{p}_2$. From (4) it follows that for any $\underline{p}$, $V^1(p \mid \underline{p}, \overline{p}_1) \leq V^1(p \mid \underline{p}, \overline{p}_2)$. There are two cases. In the first case,, $p^a\left(\underline{p}_2, \overline{p}\right) \leq \underline{p}$. In this case, the solution is given by the intersection between the line $-(1-q)p$, which is decreasing in p (see Figure 1) and the convex part of $V^1(p \mid \underline{p}, \overline{p})$. Therefore, the intersection point with $V^1(p \mid \underline{p}, \overline{p}_1)$ must be (weakly) higher than that with $V^1(p \mid \underline{p}, \overline{p}_2)$, and the monotonicity of $p^a\left(\underline{p}, \overline{p}\right)$ follows. In the second case $p^a\left(\underline{p}, \overline{p}_2\right) = \underline{p}$, it must be the case that $p^a\left(\underline{p}, \overline{p}_1\right) = \underline{p}$. Monotonicity of $p^c\left(\underline{p}, \overline{p}\right)$ follows analogously. ■

Proof of Proposition 2

Part 1. Suppose that $p^a \equiv p^a(q;k)$ and $p^c \equiv p^c(q;k)$ are the unique equilibrium interior thresholds for preference parameter q and cost k. Directing our attention to p^a, it must be the case that first order conditions hold:

$$\frac{\partial U(q;p^a,p^c)}{\partial p^a} = -q\left(1-\mathbb{E}\left(p|p^c\right)\right)\frac{\partial \Pr(p^c \text{ first} \mid p^a,p^c)}{\partial p^a} -$$
$$-\left(1-q\right)\frac{\partial\left[\mathbb{E}\left(p|p^a\right)\Pr(p^a \text{ first} \mid p^a,p^c)\right]}{\partial p^a} - k\frac{\partial T(p^a,p^c)}{\partial p^a} = 0$$

Second order conditions must hold as well, so that $\frac{\partial^2 U(q;p^a,p^c)}{\partial (p^a)^2} < 0$ (the inequality is strict from uniqueness of the Wald solution).

Notice that, from the definition of $\Pr(p^x \text{ first}|\ p^a,p^c)$ and $\mathbb{E}\left(p|p^x\right)$ for $x = a,c$, it follows that $\frac{\partial \Pr(p^a \text{ first}|p^a,p^c)}{\partial p^a} \geq 0$, $\frac{\partial \Pr(p^c \text{ first}|p^a,p^c)}{\partial p^a} \leq 0$ and $\frac{\partial \mathbb{E}(p|p^a)}{\partial p^a} \geq 0$. Therefore, for sufficiently small $\varepsilon > 0$, $\frac{\partial U(q+\varepsilon;p^a,p^c)}{\partial p^a} \geq 0$.

From the second order condition, if follows that in order to satisfy the first order condition for $q+\varepsilon$ when we fix p^c, the threshold p^a must increase.

From Lemma 2, we can iterate on best responses and get that the optimal threshold $p^a(q+\varepsilon;k) \geq p^a = p^a(q;k)$. Similar arguments follow for the threshold p^c.

Part 2. The cost k does not affect the payoffs from stopping and taking a decision (the lines $-(1-q)p$, and $-q\left(1-p\right)$ in figure 1). However, as k increases, the continuation value $V^1\left(p\right)$ decreases point-wise. Since $p^a(q;k), p^c(q;k)$, satisfy

$$V^1(p^a(q;k)) = -(1-q)p^a(q;k) \quad \text{and} \quad V^1(p^c(q;k)) = -q(1-p^c(q;k)),$$

the comparative statics with respect to k follows. ■

Proof of Lemma 3

In order to stress the dependence on preference parameters, we use $\left(p^a\left(\underline{p},\overline{p};q\right), p^c\left(\underline{p},\overline{p};q\right)\right)$ to denote the solution to the constrained problem (4) for an agent with preference parameter q. Consider then any candidate equilibrium defined by thresholds p_*, p^* such that $\underline{p} = p^a\left(p_*,p^*;q_{n-R_d+1}\right)$, and $\overline{p} = p^c\left(p_*,p^*;q_{R_d}\right)$. By Corollary 1, the best responses $p^a\left(p_*,p^*;q\right)$ and $p^c\left(p_*,p^*;q\right)$ are increasing in q. This means that, when $p \geq \overline{p}$, $p \geq p^c(p_*, p^*; q)$ for at least R_d agents, and, analogously, when $p \leq \underline{p}$, $p \leq p^a(p_*, p^*; q)$ for at least R_d agents, so that in both cases there is a quorum for stopping deliberation whenever $p \leq \underline{p}$ or $p \geq \overline{p}$. It is also clear that whenever p is in (p_*, p^*) there is no such quorum. It follows that, in equilibrium, in must be the case that $p_* = p^a(p_*, p^*; q_{n-R_d+1})$, and $p^* = p^c(p_*, p^*; q_{R_d})$, as required. ■

Proof of Lemma 4

As k decreases to zero, for any $q \in (0,1)$, $p^a(q;k)$ converges to zero and $p^c(q;k)$ converges to one: as information collection becomes extremely cheap, all types of jurors demand a high degree of confidence before either convicting or acquitting. Thus, for any $0 < p_1 < p_2 < 1$, there is a k such that, in the selected equilibrium, $p_* < p_1$, and $p^* > p_2$. ■

Proof of Proposition 4

Part 1. Consider an equilibrium $p_*(R_d, R_v)$, $p^*(R_d, R_v)$ with $R_v \leq R_d$. Thus, pivotal jurors at the deliberation stage are $q_{n-R_d+1} \leq q_{n-R_v+1}$ and $q_{R_d} \geq q_{R_v}$. By the construction of optimal thresholds, $p_*(R_d, R_v) \leq q_{n-R_d+1}$ and $p^*(R_d, R_v) \geq q_{R_d}$. Consider any p such that deliberation terminates in equilibrium: we have $p \leq p_*(R_d, R_v) \leq q_{n-R_d+1} \leq q_{n-R_v+1}$ and $p \geq p^*(R_d, R_v) \geq q_{R_d} \geq q_{R_v}$ so that whenever there is a quorum for stopping deliberation there is also a quorum for taking a decision.

Part 2. This is an immediate consequence of Lemma 4. ■

Proof of Lemma 5

Suppose there are two symmetric threshold equilibria: (p_*, p^*) and $(\tilde{p}_*, \tilde{p}^*)$. Suppose $p_* < \tilde{p}_*$. From the monotonicity captured in Lemma 2, it must be the case that $p^* \leq \tilde{p}^*$. This would imply $\tilde{p}_* + \tilde{p}^* > p_* + p^* = 1$, in contradiction to the equilibrium $(\tilde{p}_*, \tilde{p}^*)$ being symmetric. ■

Proof of Proposition 5

Part 1. Assume by way of contradiction that, for $\delta > \delta'$, the symmetric equilibria corresponding to δ and δ' satisfy $p_*\left(\delta'\right) < p_*\left(\delta\right)$ and $p^*\left(\delta'\right) > p^*\left(\delta\right)$. By Lemma 1, the best response p^a to $p^*\left(\delta\right)$ for the juror with preferences $\frac{1}{2} - \delta'$ must be such that $p^a < p_*\left(\delta'\right) < p_*\left(\delta\right)$. But since $p_*(\delta)$ is a best response to $p^*(\delta)$ for the juror with preferences $\frac{1}{2} - \delta$, this violates monotonicity of (constrained) best responses in q (Corollary 1).

Part 2. Note that Part 1 and monotonicity of thresholds with respect to q together imply that $p_*\left(\delta\right) < p^a\left(\frac{1}{2} + \delta\right)$ and $p^*\left(\delta\right) > p^c\left(\frac{1}{2} - \delta\right)$. By Lemma 2, this implies that $p^c\left(\frac{1}{2} - \delta\right) > p_*\left(\delta\right)$. Inequalities are strict for interior equilibria. ■

Proof of Proposition 6

Part 1. Consider first voting rule $R_v = R_d$, and an associated symmetric equilibrium $p_*\left(R_d, R_v; k\right)$, $p^*\left(R_d, R_v; k\right)$. This equilibrium is unique by Lemma 5. Let $\underline{k}$ be such that $p_*\left(R_d, R_v; \underline{k}\right) = q_{n-\tilde{R}_v+1}$, $p^*\left(R_d, R_v; \underline{k}\right) = q_{\tilde{R}_v}$ a single such $\underline{k}$ is sufficient because of symmetry.[32] Thus, when the cost is $\underline{k}$, the pivotal voters under rule $\tilde{R}_v$ are just indifferent between voting to acquit and voting to convict, When k is larger than $\underline{k}$, $p_*\left(R_d, R_v; k\right)$, $p^*\left(R_d, R_v; k\right)$ move further inwards (because, by Proposition 2, all best response thresholds involve acquiring less information) and therefore would induce a hung jury under $\tilde{R}_v$. Now assume that $k = \underline{k} + \varepsilon$. For ε sufficiently small the unique symmetric equilibrium under rules $R_d, \tilde{R}_v$ involves extending deliberation thresholds just enough to avoid a hung jury, and for such k we have, $p_*\left(R_d, \tilde{R}_v; k\right) = q_{n-\tilde{R}_v+1}$, $p^*\left(R_d, \tilde{R}_v; k\right) = q_{\tilde{R}_v}$. To see this, note that jurors q_{n-R_d+1}, q_{R_d} are still pivotal at the deliberation stage. Any $p_* > q_{n-\tilde{R}_v+1}$ ($p^* < q_{\tilde{R}_v}$) would induce a hung jury, which is not optimal for k sufficiently close to $\underline{k}$. This reasoning holds for any k such that obtaining a verdict is better than a hung jury for the pivotal jurors at the deliberation stage. This holds as long as k is not too high, i.e., lower than some $\underline{k}$. Clearly, any $p_* < q_{n-\tilde{R}_v+1}$ cannot be a best response to any $p^* \geq q_{\tilde{R}_v}$ (by Lemma 2): there is a loss in lowering the threshold even more, especially when the opposite threshold is high.

Part 2. This is immediate as $p_*\left(\tilde{R}_d, \tilde{R}_v; k\right) \leq q_{n-\tilde{R}_d+1} = q_{n-\tilde{R}_v+1}$, and $p^*\left(\tilde{R}_d, \tilde{R}_v; k\right) \geq q_{\tilde{R}_d} = q_{\tilde{R}_v}$ since the optimal thresholds for deliberation for any type q must surround q. ■

[32] Note that exact equality may not hold with discrete signals but the proof can be easily modified to take care of this by considering the next closest points.

Proof of Proposition 7

Consider the expression for juror payoffs from equation (3). In a quasi-symmetric jury, voting over deliberation rules implies choices of symmetric equilibrium thresholds $p^*(R_d) = 1 - p_*(R_d)$ and $\Pr(p^*(R_d) \text{ first}|\, p_*(R_d), p^*(R_d)) = \Pr(p_*(R_d) \text{ first}|\, p_*(R_d), p^*(R_d))$

$$\begin{aligned} U(q; R_d) &= -q\left(1 - \mathbb{E}\left(p|p^*(R_d)\right)\right)\Pr(p^*(R_d)\,\text{first}) - (1-q)\,\mathbb{E}\left(p|p_*(R_d)\right)\Pr(p_*(R_d)\ \text{ first}) - \\ &\quad -kT(p_*(R_d), p^*(R_d)), \\ &= -p_*(R_d)\Pr(p_*(R_d)\ \text{ first}) - kT(p_*(R_d), (1 - p_*(R_d))). \end{aligned}$$

This expression shows that preferences over deliberation rules are independent of q. To show that all jurors prefer the least inclusive deliberation rule, note that if a juror $q = 1/2$ exists, for $R_d = n/2$, this juror with $q = 1/2$ deliberation functions as if he were a dictator, so $R_d = 1/2$ is ideal for this juror. Since all other jurors share his preferences over deliberation rules, $R_d = 1/2$ must be optimal for everyone else. ■

Proof of Proposition 8

Given rules R_d and R_v, payoffs to a juror with preference q are given by:

$$\begin{aligned} U(R_d, R_v; q) &= -q\left(1 - \mathbb{E}\left(p_t|p_t \geq q_{R_v}\right)\right)\Pr\left(p_t \geq q_{R_v}\right) \\ &\quad - (1-q)\,\mathbb{E}\left(p_t|p_t < q_{n-R_v+1}\right)\left(\Pr\left(p_t < q_{n-R_v+1}\right)\right) \\ &\quad + U(H)\left(\Pr\left(q_{n-R_v+1} < p_t < q_{R_v}\right)\right). \end{aligned}$$

With symmetric juries, $q_{n-R_v+1} = 1 - q_{R_v}$, $\mathbb{E}\left(p_t|p_t < q_{n-R_v+1}\right) = 1 - \mathbb{E}\left(p_t|p_t \geq q_{R_v}\right)$, and $\Pr\left(p_t < q_{n-R_v+1}\right) = \Pr\left(p_t \geq q_{R_v}\right)$. Therefore,

$$U(R_d, R_v) = \mathbb{E}\left(p_t|p_t < q_{R_v}\right)\Pr\left(p_t < q_{n-R_v+1}\right) + U(H)\left(\Pr\left(q_{n-R_v+1} < p_t < q_{R_v}\right)\right).$$

This expression is independent of q. Thus, jurors are unanimous in their deliberation votes, implying that the deliberation rule R_d is irrelevant. However, the decision rule R_v does matter: a larger R_v raises the probability of a hung jury. This feeds back into the optimal sample size (for the unanimous jurors). Thus, a larger R_v implies more information collection. ■

References

[1] Albrecht J., A. Anderson, and S. Vroman (2010), "Search by Committee," *Journal of Economic Theory*, Vol. 145(4), pages 1386-1407.

[2] Austen-Smith, D. and T. Feddersen (2005), "Deliberation and Voting Rules," In *Social Choice and Strategic Decisions: Essays in Honor of Jeffrey S. Banks*, edited by David Austen-Smith and John Duggan, Springer-Verlag.

[3] Austen-Smith, D. and T. Feddersen (2006), "Deliberation, Preference Uncertainty, and Voting Rules," *American Political Science Review*, Vol. 100(2), pages 209-217.

[4] Baldwin J. and M. McConville (1980), "Juries, Foremen, and Verdicts," *British Journal of Criminology*, Vol. 20(1), pages 34-44.

[5] Bognar, K., M. Meyer-ter-Vehen, and L. Smith (2009), "A Conversational War of Attrition," mimeo.

[6] Compte O., and P. Jehiel (2010) "Bargaining and Majority Rules: A Collective Search Perspective," *Journal of Political Economy*, Vol. 118(2), pages 189-221.

[7] Coughlan P. (2000), "In Defense of Unanimous Jury Verdicts: Mistrials, Communication, and Strategic Voting," *American Political Science Review*, Vol. 94(2), pages 375-393.

[8] De Groot, M. H. (1970), *Optimal Statistical Decisions*, McGraw-Hill.

[9] Devine, D. J., L. D. Clayton, B. B. Dunford, R. Seying, and J. Pryce (2001), "Jury Decision Making: 45 Years of Empirical Research on Deliberating Groups," *Psychology, Public Policy, and Law*, Vol. 7(3), pages 622-727.

[10] Eso, P. and Y. Fong (2008), "Wait and See: A Theory of Communication Over Time," mimeo.

[11] Feddersen, T. and W. Pesendorfer (1998), "Convicting the Innocent: the Inferiority of Unanimous Jury Verdicts Under Strategic Voting," *The American Political Science Review,* Vol. 92(1) pages 23-35.

[12] Gerardi D. and L. Yariv (2007), "Deliberative Voting," *Journal of Economic Theory*, Vol. 134 pages 317-338

[13] Gerardi D. and L. Yariv (2008), "Information Acquisition in Committees" *Games and Economic Behavior*, Vol. 62, pages 436-459.

[14] Goeree J. and L. Yariv (2010), "An Experimental Study of Collective Deliberation," *Econometrica*, forthcoming.

[15] Harrison, J. M. (1985), *Brownian Motion and Stochastic Flow Systems*, John Wiley and Sons, New York.

[16] Hannaford P., V. Hans, N. Mott, and T. Munsterman (1999), "The Timing of Opinion Formation by Jurors in Civil Cases: an Empirical Examination," *Tennessee Law Review*, Vol. 67, pages 627-652.

[17] Hans V. (2001), "The Power of Twelve: The Impact of Jury Size and Unanimity on Civil Jury Decision Making," *Delaware Law Review*, Vol. 4(1), pages 1-31.

[18] Hans V. (2007), "Deliberation and Dissent: *12 Angry Men* versus the Empirical Reality of Juries," *Chicago-Kent Law Review*, Vol. 82, pages 579-589.

[19] Hans, V., P. Hannaford-Agor, N. Mott, and T. Musterman (2003), "The Hung Jury: *The American Jury*'s Insights and Contemporary Understanding," *Criminal Law Bulletin*, Vol. 39, pages 33-50.

[20] Kalven H. and H. Zeisel (1966), *The American Jury*, Little Brown, Boston.

[21] Li, H. and W. Suen (2009), "Decision-making in Committees," *Canadian Journal of Economics*, forthcoming.

[22] Meirowitz, A. (2006), "Designing Institutions to Aggregate Private Beliefs and Values," *Quarterly Journal of Political Science*, Vol. 1(4), pages 373-392.

[23] Moscarini, G. and L. Smith (2001), "The Optimal Level of Experimentation," *Econometrica*, Vol. 69(6), pages 1629-1644.

[24] Messner, M. and M. Polborn (2009), "The Option to Wait in Collective Decisions," mimeo.

[25] Persico N. (2004), "Committee Design with Endogenous Information," *Review of Economic Studies*, Vol. 71(1), pages 165-194.

[26] Sommers S. (2006), "On Racial Diversity and Group Decision Making: Identifying Multiple Effects of Racial Composition on Jury Deliberations," *Journal of Personality and Social Psychology*, Vol. 90, pages 597-612. .

[27] Strulovici B. (2010), "Learning While Voting: Determinants of Collective Experimentation," *Econometrica*, Vol. 78(3), pages 933-971.

[28] Wald, Abraham (1947a), "Foundations of a General Theory of Sequential Decision Functions," *Econometrica*, Vol. 15(4), pages 279-313.

[29] Wald, Abraham (1947b), *Sequential Analysis*, John Wiley and Sons, New York.