Expert Information and Majority Decisions*

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Abstract

This paper shows theoretically and experimentally that hearing expert opinions can be a double-edged sword for collective decision making. We study a majoritarian voting game of common interest where committee members receive not only private information, but also expert information that is more accurate than private information and observed by all members. In theory, there are Bayesian Nash equilibria where the committee members' voting strategy incorporates both types of information and access to expert information enhances the efficiency of the majority decision. However, there is also a class of potentially inefficient equilibria where a supermajority always follow expert information and the majority decision does not aggregate private information. In the laboratory, the majority decisions and the subjects' voting behaviour were largely consistent with those in the class of inefficient equilibria. We found a large efficiency loss due to the *presence* of expert information especially when the committee size was large. We suggest that it may be desirable for expert information to be revealed only to a subset of committee members.

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1 Introduction

When collective decisions are made through voting, typically each voter has not only private information known solely to themselves but also public information observed by all voters. Examples of commonly held information in collective decision making include "expert" opinions solicited by a committee, shared knowledge in a board meeting that has emerged from pre-voting deliberation, and evidence presented to a jury. Such information may well be superior to the private information each individual voter has, and if so, it would be natural to expect that voting behaviour should incorporate the public information at least to some extent.

Meanwhile, such public information is rarely perfect, and in particular expert opinions are often alleged to have excessive influence on decision making. For example, recently the IMF's advice to the governments of some highly indebted countries have heavily influenced their parliamentary and cabinet decisions for austerity. However, the IMF's expertise has been questioned by specialists in monetary policy, and it has been reported that the IMF itself has admitted that they may have underestimated the impact of their austerity measure in Greece.[1] Financial deregulations in the 1990s seem to have been prompted by endorsements from financial experts at the time, but some politicians reflect that in retrospect they may have followed expert opinions too naively.[2] How would collective decision making through voting be influenced by shared information? If commonly observed expert information is better than the information each voter has, would the presence of such expert information improve the quality of the collective decision? Can expert information have "too much" influence?

This paper addresses these questions theoretically and experimentally, by introducing a public signal into an otherwise classical Condorcet jury setup with majority rule. The public signal is observed by all voters and assumed to be superior to the private signal each voter receives. We call such a public signal "expert information".[3]

The first part of the paper presents a majoritarian voting game with expert information and identifies three types of equilibria of interest, namely i) the symmetric mixed strategy equilibrium where each member randomizes between following the private and public signals should they disagree; ii) the asymmetric pure strategy equilibrium where a certain number of members always follow the public signal while the others always follow the private signal; and iii) a class of equilibria where a supermajority and hence the committee decision always follow the expert signal.[4] We find that in the first two

[1] "IMF 'to admit mistakes' in handling Greek debt crisis and bailout", *Guardian*, 4 June 2013, `http://www.guardian.co.uk/business/2013/jun/05/imf-admit-mistakes-greek-crisis-austerity`

[2] "Gordon Brown admits 'big mistake' over banking crisis", *BBC News*, 13 March 2013, `http://www.bbc.co.uk/news/business-13032013`

[3] As we will discuss later in Section 2, the public signal can also be thought of as shared information (common prior) emerged through pre-voting deliberation.

[4] While the voters may ignore their private information completely, they cannot ignore the expert information completely in equilibrium. That is, voting according only to their private signal is never an

equilibria, the expert signal is collectively taken into account in such a way that it enhances the efficiency (accuracy) of the committee decision, and a fortiori the Condorcet jury theorem (CJT) holds so that as the size of the committee becomes larger the probability that the decision is correct becomes higher and goes to 1. However, in the third type of equilibria, private information is not reflected in the committee decision and the efficiency of committee decision is identical to that of public information, which may well be lower than the efficiency the committee could achieve without expert information. In other words, the introduction of expert information might reduce efficiency in equilibrium.

Motivated by the possibility that expert information can enhance or diminish the efficiency of equilibrium committee decisions, we conducted a laboratory experiment to study the effect of expert information on voting behaviour and majority decisions. Of particular interest is to see whether voters can play an efficient equilibrium, not least because the efficient equilibria seem to require sophisticated coordination among voters. Specifically, we set the accuracies of the signals in such a way that the expert signal is more accurate than each voter's private signal but less accurate than what the aggregation of the private signals can achieve by sincere voting without the expert signal. Such parameter values seem plausible in that the expert opinion should be taken into account but should not be decisive on its own. At the same time, they entail the possibility that expert information may indeed be welfare reducing if more than a half of the voters follow the expert obediently.

The second part of this paper reports the results from the experiment. We found that the voters followed the expert signal much more frequently than they should in the efficient equilibria. Specifically, the majority decisions followed the expert signal most of the time, which is consistent with the class of obedient equilibria mentioned above. Another interesting finding is the marked heterogeneity in voting behaviour. While there were voters who consistently followed their private signal and ignored the public signal, a significant portion of voters followed the expert signal most of the time. We will argue that the voters' behaviour in our data can be best described as that in an obedient equilibrium where a supermajority (and hence the decision) always follow the expert signal so that no voter is pivotal.

Even if the committees in the laboratory followed expert information most of the time, this does not necessarily imply that introducing expert information is harmful, because in the absence of expert information the voters may not play the (efficiency maximizing) equilibrium strategy of sincere voting. Along with the treatments with both private and expert information, we also ran control treatments where each voter received a private signal only, in order to compare the observed efficiency of the committee decisions with and without expert information. We found that for seven-person

equilibrium, since if a voter knows that all the others will follow their private signals, he deviates and follows the expert signal, which is by assumption superior to his private signal.

committees the difference in the efficiency between the treatment and the control is insignificant, largely due to some non-equilibrium behaviour (i.e., voting against private information) in the control treatment which reduced the benchmark efficiency. However, for fifteen-person committees, those without expert information performed much better than those with expert information and the difference is significant, suggesting that expert information was indeed harmful.

Our theoretical and experimental results suggest that, from the viewpoint of a social planner who decides whether to and how to provide a committee with expert information, creating an equilibrium with higher efficiency does not necessarily mean it is selected among other equilibria, and in particular there is a possibility that provision of public information may lead to an inefficient equilibrium being played.[5] This concern seems particularly relevant when an inefficient equilibrium is simple and intuitive to play, like the obedient equilibrium in our model, while the efficient equilibrium requires subtle coordination. A natural solution to this problem would be to rule out inefficient equilibria, if possible. In our model, if the expert information is revealed only to a small subset of voters, the obedient equilibrium where a supermajority always follow the expert can be ruled out. Moreover, if the size of the subset is optimally chosen, there will be a simple *and* efficient equilibrium, where this subset of the voters receive and vote according to the expert signal, and the others who do not receive the expert information vote according to their own private signal. Intuitively, such selective disclosure prevents an expert from having too much influence. Alternatively, if an expert opinion is heard by all members, a coordination procedure such as role assignment (e.g., who should follow the expert information and who should ignore it) may lead to an efficient equilibrium. A contribution of this paper in this regard is to demonstrate that, without a coordination device, an efficient equilibrium may not necessarily be played even in a game of common interest especially when there is a simple but inefficient equilibrium.

In their seminal paper Austen-Smith and Banks (1996) first introduced game-theoretic equilibrium analysis to the Condorcet jury with independent private signals. They demonstrated that sincere voting (in pure strategy) is not generally consistent with equilibrium behaviour. McLennan (1998) and Wit (1998) studied symmetric mixed strategy equilibria in the model of Austen-Smith and Banks (1996) and showed that the CJT holds in equilibrium for majority and super-majority rules (except for unanimity rule). The experimental study on strategic voting was pioneered by Guarnaschelli et al. (2000) who tested the model of Austen-Smith and Banks (1996) and found that the subjects' behaviour was largely consistent with the theory. Focusing on unanimity rule, Ali et al. (2008) found that the findings by Guarnaschelli et al. (2000) are fairly robust to voting protocols such as the number of repetitions and timing of voting (simultaneous or se-

[5] As in standard models of voting, our model also has equilibria that are implausible from the view point of application and efficiency, such as uninformative equilibrium where all committee members vote for a particular option regardless of their private signal, and equilibrium where all members the vote against the expert signal.

quential). The present paper focuses on majority rule, but examines the effect of public information on voting behaviour and outcomes.

The literature on deliberation in voting has studied public information endogenously generated by voters sharing their otherwise private information through pre-voting deliberation (e.g., Coughlan, 2000; Austen-Smith and Feddersen, 2005; and Gerardi and Yariv, 2007). In these models, once a voter reveals his private information credibly, he has no private information. Goeree and Yariv (2011) found in a laboratory experiment that deliberation diminishes differences in voting behaviour across different voting rules.

Battaglini et al. (2010) and Morton and Tyran (2011) report results from experiments where voters are asymmetrically informed, to study how the quality of the private signal affects their decision to abstain, in the spirit of the model of Feddersen and Pesendorfer (1996).[6] The quality of the information each voter has in our framework also varies according to whether the private and expert signals agree, in which case they provide strong information about the state; or they disagree, in which case the uncertainty about the state becomes relatively high. However, we do not allow voters to abstain, and more importantly our primary interest is in the combination of private and public information, which is fundamentally different from private information with different accuracy levels in terms of the effect on the voters' strategic choice, not least because the public signal in our framework represents a perfectly correlated component of the information each voter has.

While we focus on simultaneous move voting games, the inclination to ignore private information in favour of expert information is reminiscent of rational herding in sequential decisions. In the original rational herding literature (e.g., Banerjee, 1992; Bikhchandani, Hirshleifer, and Welch, 1992) each player's payoff is assumed to be determined only by his decision but not by others. Dekel and Piccione (2000) and Ali and Kartik (2012) are among the papers that theoretically study sequential voting in collective decision making where payoffs are intrinsically interdependent. Unlike the expert signal in our setup, which is exogenously given to all voters, public information in their models is generated endogenously by the observed choices of earlier voters. Dekel and Piccione (2000) show that the multiple equilibria include an equilibrium where all voters vote sincerely, which is informationally efficient. Ali and Kartik (2012) identify equilibria that exhibit herding whereby after observing some votes, the rest vote according to what the earlier votes indicate, regardless of their private information. Hung and Plott (2001) conducted a laboratory experiment on sequential voting with majority rule. They found that some herding indeed occurred, resulting in inefficiency compared to sincere voting.

Our model and experimental design are based on the uniform prior with expert information. This structure is theoretically isomorphic to the case of the canonical

[6]Bhattacharya et al. (2014) study a related experimental setup but with costly voting.

Condorcet jury model without public information but with a common non-uniform prior belief. Thus while we incorporate expert information into the voters' Bayesian updating explicitly to gain relevant intuition, the symmetric mixed strategy equilibrium we derive in this paper can be thought of as a special case of the one shown by Wit (1998) who solved for the equilibrium without assuming the uniform prior. However, we also explicitly derive an asymmetric pure strategy equilibrium and its optimality, which has not been shown previously in the literature. In doing so, we draw an important link between our fully strategic setup and the optimal voting rule with heterogeneously informed but non-strategic voters studied by Nitzan and Paroush (1982).[7]

The important advantage of adopting the uniform prior and expert information, rather than a non-uniform prior without expert information, is that we are able to ask a potentially useful policy question as to whether to, and how to bring expert opinions into collective decision making. Our experiment is based on this premise, and provides us with practical implications such as the possibility that the introduction of expert information can reduce efficiency, even though theoretically it can enhance welfare if the voters coordinate to play an efficient equilibrium. It would be impossible to address such an issue if we adopted a non-uniform prior analogue without expert information, because in practice the prior belief is seldom a choice variable in itself, while decision making bodies can usually choose whether to listen to expert opinions.

The rest of this paper is organized as follows. The next section presents our model, and its equilibria are studied in Section 3. Section 4 presents the experimental design, and Section 5 discusses the results. Section 6 concludes.

2 Model

Consider a committee that consists of an odd number of agents $n \in N = \{1, 2, .., n\}$. Each agent simultaneously casts a costless binary vote, denoted by $x_i = \{A, B\}$, for a collective decision $y \in Y = \{A, B\}$. The committee decision is determined by majority rule. The binary state of the world is denoted by $s \in S = \{A, B\}$, where both events are ex ante equally likely $\Pr[s = A] = \Pr[s = B] = \frac{1}{2}$. The members have identical preferences $u_i : Y \times S \to \mathbb{R}$ and the payoffs are normalized without loss of generality at 0 or 1. Specifically we denote the vNM payoff by $u_i(y, s)$ and assume $u_i(A, A) = u_i(B, B) = 1$ and $u_i(A, B) = u_i(B, A) = 0$, $\forall i \in N$. This implies that the agents would like the decision to be matched with the state.

Before voting, each agent receives two signals. One is a private signal about the state $\sigma_i \in K = \{A, B\}$, for which the probability of the signal and the state being matched is given by $\Pr[\sigma_i = A \mid s = A] = \Pr[\sigma_i = B \mid s = B] = p$, where $p \in (1/2, 1]$. We

[7]While most theoretical studies on strategic voting focus on symmetric strategies, Persico (2004) establishes the optimality of asymmetric strategy equilibrium in a voting game related to ours. However, he does not give an explicit solution for such an equilibrium.

also have $\Pr[\sigma_i = A \mid s = B] = \Pr[\sigma_i = B \mid s = A] = 1 - p$.

In addition to the private signal, all agents in the committee observe a common public signal $\sigma_E \in L = \{A, B\}$, which is assumed to be more accurate than each agent's individual signal. Specifically, we assume $\Pr[\sigma_E = A \mid s = A] = \Pr[\sigma_E = B \mid s = B] = q$ and $\Pr[\sigma_E = A \mid s = B] = \Pr[\sigma_E = B \mid s = A] = 1 - q$, where $q > p$. The distributions of the two signals are independent.

The public signal in our model has natural interpretations. It can be thought of as expert information given to the entire committee as in, e.g. congressional hearings. Briefing materials presented to and shared in the committee would also have the same feature. Alternatively, it may capture shared knowledge held by all agents as a result of pre-voting deliberation. In that case, the private signal represents any remaining uncommunicated information held by each agent, which is individually inferior to shared information.[8] Throughout this paper we often refer to the public information as expert information.

The timing of our voting game is summarized as follows:

1. Nature determines the state of the world;
2. Each agent observes private and public signals about the state;
3. Each agent votes;
4. Majority decision is implemented and payoffs are realized.

In the absence of the public signal, there exists a sincere voting equilibrium such that $x_i = \sigma_i$ for any i and the Condorcet Jury Theorem holds (Austen-Smith and Banks, 1996). In what follows we study Bayesian Nash equilibria of the game in which the agents also share expert information. Before doing so let us define some key concepts.

Let $v_i : K \times L \to [0, 1]$ denote the probability of an agent voting for the state her private signal $\sigma_i \in K = \{A, B\}$ indicates, given the private signal and the public signal $\sigma_E \in L = \{A, B\}$. For example, $v_i(A, B)$ is the probability that agent i votes for A given that his private signal is A and the public signal is B.

Definition 1. A voting strategy v_i is *symmetric* if $v_i = v$, $\forall i \in N$.

When we derive equilibria of the game later in Section 3, we first focus on symmetric strategy equilibria (Section 3.1) and then consider asymmetric strategy equilibria (Section 3.2).

[8] Suppose that every agent receives two independent signals σ_i^1 and σ_i^2 with accuracy p^1 and p^2, respectively, but there is no public signal ex ante. Assume also that due to time, cognitive or institutional constraints, only the first piece of information (σ_i^1) can be shared through deliberation in the committee before voting. If $\{\sigma_1^1, \sigma_2^1, ..., \sigma_n^1\}$ are revealed to all agents, they collectively determine the accuracy of public information q, while the accuracy of remaining private information for each agent $\{\sigma_1^2, \sigma_2^2, ..., \sigma_n^2\}$ is that of the second signal p^2. The collective accuracy of the shared signals depends on the realization of $\{\sigma_1^1, \sigma_2^1, ..., \sigma_n^1\}$ and we may not necessarily have $q > p^2$.

We use the term *responsive* to refer to any voting behaviour v_i that varies according to different combinations of the signals.

Definition 2. A voting strategy v_i is *responsive* if $v_i(\sigma_i, \sigma_E) \neq 1 - v_i(\sigma_i^{'}, \sigma_E)$ for $\sigma_i \neq \sigma_i^{'} \in K, \sigma_E \in L$.

This rules out *uninformative* strategies where an agent votes for A or B with a fixed probability regardless of the signals.

Since each agent in our model receives two signals, we formalize three classes of strategies, namely i) one where v_i depends only on the private signal; ii) one where v_i depends only on the public signal; and iii) the other where v_i depends on both the private and public signals.

Definition 3. A voting strategy v_i is *individually informative* if $v_i(\sigma_i, \sigma_E) = 1$, $\forall \sigma_i \in K, \sigma_E \in L$.

An individually informative strategy is a pure strategy analogous to informative (or "sincere") voting in the standard voting literature with private information, where an agent votes for what the private signal indicates.

Meanwhile there is another type of pure strategy where the agent reacts only to the public signal.

Definition 4. A voting strategy v_i is *obedient* if $v_i(A, B) = v_i(B, A) = 0$ and $v_i(A, A) = v_i(B, B) = 1$.

An obedient strategy is the pure strategy where an agent votes for what the public signal indicates with probability 1, regardless of his private signal.

Since each agent has signals (private and public) that are drawn independently, they may disagree with each other. We formalize the notion of responding to both signals under disagreement as follows:

Definition 5. A voting strategy v_i is *dually responsive* if $v_i(A, \sigma_E) \neq v_i(B, \sigma_E)$ $\forall \sigma_E \in L$, and at least $v_i(A, B) \in (0, 1)$ or $v_i(B, A) \in (0, 1)$.

When both signals disagree and a strategy is dually responsive, the agent follows neither of them with probability 1.

As in the literature on strategic voting, each agent's optimal action depends on the comparison of his expected payoffs in the event where he is pivotal.

Definition 6. $Piv(v_{-i})$ denotes the event where agent i is pivotal, given his strategy v_i and the others' strategies v_{-i}.

Throughout this paper we study the equilibria of the voting game with fully rational agents, and the solution concept we use is Bayesian Nash equilibrium:

Definition 7. A Bayesian Nash equilibrium of the game is a strategy profile v^*, such that

$$E[u_i|v_i^*, Piv(v_{-i}^*), \sigma_i, \sigma_E] \geq E[u_i|v_i, Piv(v_{-i}^*), \sigma_i, \sigma_E], i \in N, v_i \in X \times S, \sigma_i \in K, \sigma_E \in L. \tag{1}$$

The efficiency of the committee decision making with expert information is measured in comparison to the efficiency under sincere voting in the absence of expert information.

Definition 8. Suppose each of n agents receives a private signal only (with accuracy $p > 1/2$) and votes according to the signal. The probability that the majority decision matches the state is denoted by

$$P_C(p, n) \equiv \sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} p^k (1-p)^{n-k}.$$

Needless to say the Condorcet Jury Theorem states that $P_C(p, n) \to 1$ as $n \to \infty$. In the absence of a public signal, individually informative voting is also the most efficient Bayesian Nash equilibrium (Austen-Smith and Banks, 1996). In what follows efficiency is measured in terms of the ex ante probability that the majority decision matches the state given a strategy profile.

3 Equilibrium Predictions

In this section we study implications of the coexistence of private and public signals on equilibrium voting behaviour. But let us first note that, as in most models in the voting literature, our model also has "uninformative" equilibria where all agents vote for one of the alternatives regardless of the signals and the outcome is deterministic. This holds true because no individual agent can be pivotal if the others are known to vote for the option and hence no agent influences the outcome individually.

In what follows we consider equilibria in which voting behaviour and the outcome depend on the signals the agents observe. Specifically, we focus on how agents vote depending on whether their private and public signals agree or disagree, i.e., $v_i(A, A) = v_i(B, B)$ and $v_i(A, B) = v_i(B, A)$ for any i. That is, the labelling of the state is assumed irrelevant, in line with the feature that the payoffs depend only on whether the decision matches the state, but not on which state was matched or mismatched.

3.1 Symmetric strategies

Let us focus our attention to symmetric strategy equilibria first, where $v_i(A, A) = v_i(B, B) \equiv \alpha$ and $v_i(B, A) = v_i(A, B) \equiv \beta$ for any i. Note that because of the symmetry of the model with respect to A and B, we can consider the cases of $\sigma_E = A$ and $\sigma_E = B$ as two independent and essentially identical games, where only the labelling differs. We start by observing that the presence of expert information upsets the individually informative equilibrium, where every agent votes according to his own signal only.

Proposition 1. *Individually informative voting is not a Bayesian Nash equilibrium.*

Proof. See Appendix I. □

The proposition has a straightforward intuition. Suppose that an agent is pivotal and his private signal and the public signal disagree. In that event, the posterior of the agent is such that the votes from the other agents, who vote individually informatively, are collectively uninformative, since there are equal numbers of the votes for A and B. Given this, the agent compares the two signals and chooses to follow the public one as it has higher accuracy ($q > p$), but such voting behaviour breaks the individually informative equilibrium.

On the other hand, it is easy to see that there exists an equilibrium where every agent votes according the public signal and ignores their own:

Proposition 2. *Obedient voting is a Bayesian Nash equilibrium.*

Proof. Consider agent i. If all the other agents vote according to the public signal, he is indifferent to which alternative to vote for, and thus every agent adopting obedient voting is an equilibrium. □

The reasoning is similar to the one for the uninformative equilibria where all agents vote for the same alternative regardless of the signals and the probability of the majority decision matching the correct state is $1/2$. However, in the obedient equilibrium the outcome does reflect one of the signals in the game and thus is not completely uninformative. The equilibrium clearly outperforms the uninformative equilibria since $q > 1/2$. The same line of reasoning also leads to the following remark:

Remark 1. There exists an equilibrium where every agent votes against the public signal.

This equilibrium however seems implausible, since from $1 - q < 1/2$ it is outperformed even by the uninformative equilibria. In what follows we rule out this equilibrium.

Next we show that there exists a mixed strategy equilibrium where both private and public signals are taken into account, and observe some of its properties.

Proposition 3. *If $q \in (p, \bar{q}(p, n))$, there exists a unique dually responsive Bayesian Nash Equilibrium, where*

$$\bar{q}(p, n) = \frac{\left(\frac{p}{1-p}\right)^{\frac{n+1}{2}}}{1 + \left(\frac{p}{1-p}\right)^{\frac{n+1}{2}}}.$$

In the equilibrium, the agents whose private signal coincides with the public signal vote accordingly with probability $\alpha^* = 1$. *The agents whose private signal disagrees with the public signal vote according to their private signal with probability*

$$\beta^* = \frac{1 - A(p,q,n)}{p - A(p,q,n)(1-p)}, \text{ where } A(p,q,n) = \left(\frac{q}{1-q}\right)^{\frac{2}{n-1}} \left(\frac{1-p}{p}\right)^{\frac{n+1}{n-1}}.$$

If $q \geq \bar{q}$ *there is no dually responsive equilibrium.*

Proof. This partially follows from Wit (1998).[9] A direct proof is given in Appendix I. □

Note that in order for the mixed strategy equilibrium to exist, the accuracy of the public signal has to be lower than a threshold $\bar{q}(p,n)$. If this is the case, there are two symmetric responsive equilibria of interest, namely i) the obedient equilibrium where all agents follow the public signal; and ii) the dually responsive equilibrium in which the agents take into account both signals by mixing. Meanwhile, if the public signal is sufficiently accurate relative to the private signals, then the only responsive equilibrium is obedient.

Let us consider the efficiency of the dually responsive equilibrium in relation to that of the obedient equilibrium. This is a non-trivial question to ask, not least because the public signal introduces a type of "correlation" to the information the agents receives, and it is known that correlation of private signals leads to less efficiency. However, as the following proposition states, in the dually responsive equilibrium the agents optimally incorporate the public signal through mixing with respect to symmetric strategy profiles. That is, if a welfare maximizing social planner were to choose $\alpha \equiv v(A,A) = v(B,B)$ and $\beta \equiv v(A,B) = v(B,A)$ to maximize the probability that the majority decision matches the true state, which we denote by $P(\alpha,\beta)$, then they coincide with the equilibrium α^* and β^*.

Proposition 4. *The dually responsive equilibrium in Proposition 3 maximizes the efficiency of the majority decisions with respect to* α *and* β*.*

Proof. This follows from Theorem 1 in Wit (1998). A direct proof is given in Appendix I. □

A direct implication of Proposition 4 is that providing the committee with expert information is beneficial as long as the committee members play the symmetric mixed strategy equilibrium:

Corollary 1. *The mixed strategy equilibrium identified in Proposition 3 outperforms individually informative voting and obedient voting.*

[9] Cf. The proof of Lemma 2 in Wit (1998).

The corollary holds because individually informative voting is equivalent to $\alpha = \beta = 1$ and obedient voting $\alpha = \beta = 0$, and Proposition 4 has just shown that the mixed strategy equilibrium ($\alpha^* = 1$ and $\beta^* \in (0, 1)$) is optimal with respect to the choice of α and β.

3.2 Asymmetric strategies

So far we have focused on symmetric strategies and studied the unique dually responsive equilibrium as well as the obedient equilibrium. In this subsection we examine equilibria in asymmetric strategies. As allowing asymmetric strategies leads to a vast number of possible configurations of equilibria, we focus on i) asymmetric strategy equilibria where the majority decision is the same as that in the symmetric obedient equilibrium and ii) asymmetric pure strategy equilibrium that is unique in an intuitive set of pure strategy profiles and is optimal in the set of all strategy profiles. As in the previous subsection, we rule out non-responsive equilibria where the majority decision is independent of the signals.

3.2.1 Obedient outcome

The first type of asymmetric equilibria are a straightforward extension of the obedient equilibrium in symmetric strategies (Proposition 2) and take the following “hybrid” form:[10]

Proposition 5. *For $n \geq 5$ there exist equilibria where $(n + 1)/2 + 1$ or more agents (a supermajority) vote according to the public signal and the rest vote arbitrarily. The decision is obedient: the committee decision coincides with the public signal with probability* 1.

Proof. This directly follows from the feature that, if a supermajority always vote according to the public signal, no agent is pivotal. We have $n \geq 5$ because if $n = 3$ then $(n + 1)/2 + 1$ members following the public signal corresponds to the symmetric obedient strategy. □

Note that it is not sufficient for the equilibria to have $(n + 1)/2$ agents following the public signal, because if it is the case, these agents will be pivotal with positive probability. Clearly Proposition 5 includes a class of payoff equivalent equilibria in which some agents use pure strategies and the the others randomize:

Definition 9. A *hybrid obedient equilibrium* is an equilibrium where $n \geq 5$ and $(n + 1)/2 + 1$ or more agents (i.e. a supermajority) are obedient to the public signal and at least one of the rest adopts a non-obedient strategy.

[10]By the same token there are equilibria where $(n + 1)/2 + 1$ agents vote against the public signal, but we rule them out as they are outperformed by even by the uninformative equilibrium.

While the majority decision in the equilibrium is trivial and identical to the symmetric obedient equilibrium, the hybrid obedient equilibrium will be of significant interest in interpreting the experimental results, as we will see later.

3.2.2 Asymmetric pure strategies

Let us now consider asymmetric pure strategies for which the committee decision is affected by private signals. Let Γ be the set of all (pure, mixed and hybrid) strategy profiles. Since from Proposition 1 we know that individually informative voting is not an equilibrium, we need to consider asymmetric strategies to study responsive equilibrium in pure strategies. In what follows we focus on the strategy profiles such that the agents vote according to either the public or private signal with probability 1.

Definition 10. $M \subset \Gamma$ is the set of asymmetric pure strategy strategy profiles in which $m \in \{1, 2, ..., n-1\}$ "obedient" agents vote according to the public signal with probability 1, and $n-m$ "individually informative" agents vote according to their private signal with probability 1.

In this set of pure strategy profiles, if any agent's private signal and his public signal agree, then he votes according to the signals. The two groups (obedient and individually informative) vote differently when the signals disagree: in such cases the m "obedient" agents vote according to the public signal, while $n - m$ "individually informative" agents vote against the public signal. In what follows we establish the existence of a non-obedient equilibrium in M and its optimality in Γ. Before describing the equilibrium, it is useful to define the subset of M in which the committee decision is not obedient.

Definition 11. $\hat{M} \subset M$ is the set of pure strategy profiles where $m \in \{1, 2, ..., (n + 1)/2 - 1\}$.

The following proposition states that, unless the accuracy of the public signal q is too high relative to the accuracy of each private signal p, there is a unique equilibrium in $\hat{M}$.

Proposition 6. *Let*

$$m^* \in \mathbb{N} \cap \left(\frac{\ln[q] - \ln[1-q]}{\ln[p] - \ln[1-p]} - 1, \frac{\ln[q] - \ln[1-q]}{\ln[p] - \ln[1-p]} \right] .$$

If $m^* < (n+1)/2$ *or equivalently*

$$q < \frac{e^{\frac{n+1}{2}} \frac{p}{1-p}}{1 + e^{\frac{n+1}{2}} \frac{p}{1-p}},$$

then $m = m^*$ is the unique Bayesian Nash equilibrium in the set of strategy profiles $\hat{M}$. If $m^* \geq (n+1)/2$, then any $m \geq (n+1)/2$ in M leads to an equilibrium that is payoff equivalent to the obedient equilibrium.

Proof. See Appendix I. □

It remains to examine the efficiency of the asymmetric pure equilibrium in $\hat{M}$. In what follows we first show that if $m^* < (n+1)/2$ then it maximizes the efficiency with respect to the entire pure strategy profiles Γ. In other words, if a social planner is to choose m when q is not too large relative to p, then she will choose m^*. It then follows that the equilibrium outperforms the symmetric mixed strategy equilibrium identified in Proposition 3.

Proposition 7. *If $m^* < (n+1)/2$, then m^* uniquely maximizes the expected welfare in Γ.*

Proof. See Appendix I. □

The following corollary is a direct consequence of Proposition 7.

Corollary 2. *The asymmetric pure strategy equilibrium with m^* outperforms the sincere voting equilibrium in the absence of public information.*

The intuition is simple: suppose that only one agent always follows the public signal and the rest always follow the private signal. The efficiency under this strategy profile is higher than the efficiency under sincere voting without public information because one agent following the public signal is equivalent to this agent having a better signal since $q > p$. Therefore m^* guarantees that the welfare is higher in the asymmetric pure equilibrium with public information.

Also Proposition 7 implies the following ranking of multiple equilibria.

Remark 2. The efficiency of equilibria in the voting game with expert information, when they exist, is ranked as follows:

$$\text{non-obedient asymmetric pure eqm} \succ \text{symmetric mixed eqm} \succ \text{obedient eqm}. \quad (2)$$

We have also seen that the sincere voting equilibrium in the absence of public information can be better or worse than the obedient equilibrium, while it is always less efficient than the symmetric mixed strategy equilibrium (and hence the non-obedient asymmetric pure strategy equilibrium).[11]

[11] Let us comment on the upper bound on q for which the symmetric pure strategy equilibrium in Proposition 3 and the responsive asymmetric pure strategy equilibrium in Proposition 6 exist. It is easy to check that whether one or both of them exist simultaneously depends on p and n. Clearly both equilibria exist unless q is too high, but when q is very high, it may be that the symmetric mixed strategy equilibrium exists and the asymmetric pure strategy does not exist (, which is the case when both p and n are high) and vice versa.

To conclude this section, let us comment on the way committee members listen to expert opinions. So far we have assumed that every member hears expert information before voting, but alternatively an expert could speak to certain members of a committee only. Note that if m^* members of the committee listen to expert information, then there is an equilibrium equivalent to the most efficient equilibrium in Proposition 6, where m^* members follow the expert signal and $n - m^*$ members follow the private signal. While this selective disclosure does not change the maximum equilibrium efficiency, it eliminates the inefficient obedient equilibrium since not enough members observe the public signal for the obedient outcome. This is a theoretically trivial point: needless to say, if the agents can coordinate to play the efficient equilibrium, whether all members or only m^* of them listen to the expert is irrelevant. However, given that in reality expert opinions/testimonies are very often heard by all members of a decision making body, it would be of practical interest to ask whether this may or may not "trap" the committee in the inefficient equilibrium.

4 Experimental Design

So far we have seen that the introduction of expert information into a committee leads to multiple responsive equilibria, while ruling out the individually informative equilibrium. On one hand, we have derived equilibria where such public information is used to enhance efficiency. They require either mixing or a certain number of agents following the public signal regardless of their private signal. On the other hand, however, there are equilibria where the outcome always follows the public signal so that the CJT fails and the decision making efficiency may be reduced relative to the sincere voting equilibrium in the absence of expert information. Despite the (potentially severe) inefficiency, these equilibria seem simple to play and require very little coordination among agents.

In order to examine which equilibria best describe how people respond to expert information in collective decision making, we use a controlled laboratory experiment to collect data on voting behaviour when voters are given two types of information, private and public. The experiment was conducted through computers at the Behavioural Laboratory at the University of Edinburgh.[12] We ran four treatments, each of which had three sessions, in order to vary committee size and whether or not the subjects received public information. The variations were introduced across treatments rather than within because, as we will see shortly, we had to let our subjects play over relatively many periods, in order to ensure that for each setup the subjects have enough (random) occurrences where the private and public signals disagree. Each treatment involved either private information only or both private and public information, and each session consisted of either two seven-person committees or one fifteen-person

[12]The experiment was programmed using z-Tree (Fischbacher, 2007).

Table 1: Treatments

Treatment	Private signal	Public signal	Comm. size	No. of sessions	No. of subjects
1	yes	yes	7	3	$7 \times 2 \times 3 = 42$
2	yes	yes	15	3	$15 \times 3 = 45$
3	yes	no	7	3	$7 \times 2 \times 3 = 42$
4	yes	no	15	3	$15 \times 3 = 45$

committee. The committees made simple majority decisions for a binary state, namely which box (blue or yellow) contains a prize randomly placed before the subjects receive their signals (see Table1). The instructions were neutral with respect to the two types of information: private information was literally referred to as "private information" and expert information was referred to as "public information". After the instructions were given, the subjects were allowed to proceed to the voting game only if they gave correct answers to all short-answer questions about the instructions.

For all treatments, the prior on the state was uniform and independent in each period, and we set the accuracy of each private signal (blue or yellow) at $p = 0.65$ throughout. For the treatments with a public signal (also blue or yellow) we set its accuracy at $q = 0.7$. We presented the subjects with the accuracy of the signals ($p = 0.65$ and $q = 0.7$) clearly and explicitly in percentage terms, which was described by referring to a twenty-sided dice in order to facilitate the understanding by the subjects who may not necessarily be familiar with percentage representation of uncertainty.[13] The parameter values were chosen so as to make the potential efficiency loss from the obedient outcome large. From Proposition 6 we have $m^* = 1$ in the efficient asymmetric pure equilibrium. That is, for both treatments, in order to maximize the efficiency only one member in each committee should follow the public signal and the rest should follow their private signals.

The predicted efficiency of seven-person committees with private signals only is $P_C(0.65, 7) = 0.8002$ and that of fifteen-person committees is $P_C(0.65, 15) = 0.8868$. Thus the accuracy of the public information is above each private signal but below what the committees can collectively achieve by aggregating their private information. This implies that the obedient equilibrium is less efficient than the informative equilibrium without public information. Note that the symmetric mixed and asymmetric pure equilibria we saw earlier for committees with expert information achieve higher efficiency than $P_C(\cdot, \cdot)$ (see Corollaries 1 and 2), although the margins are small under the parameter values here. Specifically, the predicted efficiency of seven-person committees with expert information is 0.8027 and 0.8119 in the symmetric pure equilibrium, and the predicted efficiency of fifteen-person committees is 0.8878 in the symmetric mixed equilibrium and 0.8922 in the asymmetric pure equilibrium.

Note that from the theoretical viewpoint, the subjects in the treatments with both

[13]Every subject was given a real twenty-sided dice.

Table 2: Voting behaviour: subjects' choice and equilibrium predictions

		7-person committees			15-person committees		
		treatment with expert	efficient equilibrium sym.	efficient equilibrium asym.	treatment with expert	efficient equilibrium sym.	efficient equilibrium asym.
vote for private when signals disagree	overall	0.3501	0.9381	0.8571	0.3218	0.9745	0.9333
	first 30	0.3382			0.3074		
	last 30	0.3624			0.3373		
vote for signals in agreement	overall	0.9488	1	1	0.9521	1	1
	first 30	0.9523			0.9527		
	last 30	0.9454			0.9515		

types of information would have had a non-trivial decision to make when their private and public signals disagree. Otherwise (when the two signals agree), they should vote according to these signals in any of the three equilibria we are concerned with. Since the probability of receiving disagreeing signals is only 0.44 $(= 0.7 \times 0.35 + 0.3 \times 0.65)$, the voting game was run for sixty periods to make sure each subject has enough occurrences of disagreement. In every treatment the sixty periods of the respective voting game were preceded by another ten periods of the voting game with only private signals, in order to increase the complexity of information in stages for the subjects in the public information treatments.[14] We do not use the data from the first ten periods of the treatments without public signals, but it does not alter our results qualitatively.

After all subjects in a session cast their vote for each period, they were presented with a feedback screen, which showed the true state, vote counts (how many voted for blue and yellow respectively) of the committee they belong to, and payoff for the period.[15] The committee membership was fixed throughout each session.[16] This is primarily to encourage, together with the feedback information, coordination towards an efficient equilibrium.

5 Experimental Results

In this section we present our experimental results. We first discuss the individual level data to consider the change and heterogeneity of the subjects' voting behaviour in the treatments with expert information. We then examine the majority decisions in those treatments and contrast them to the equilibrium predictions. Finally we compare

[14]The subjects in the private information treatments played the same game for seventy periods but they were given a short break after the first ten periods, in order to make the main part (sixty periods) of all treatments closer.

[15]The feedback screen did not include the signals of the other agents or who voted for each colour. This is to capture the idea of private information and anonymous voting, and also to avoid information overload.

[16]In the treatments for two seven-person committees, the membership was randomly assigned at the beginning of each session.

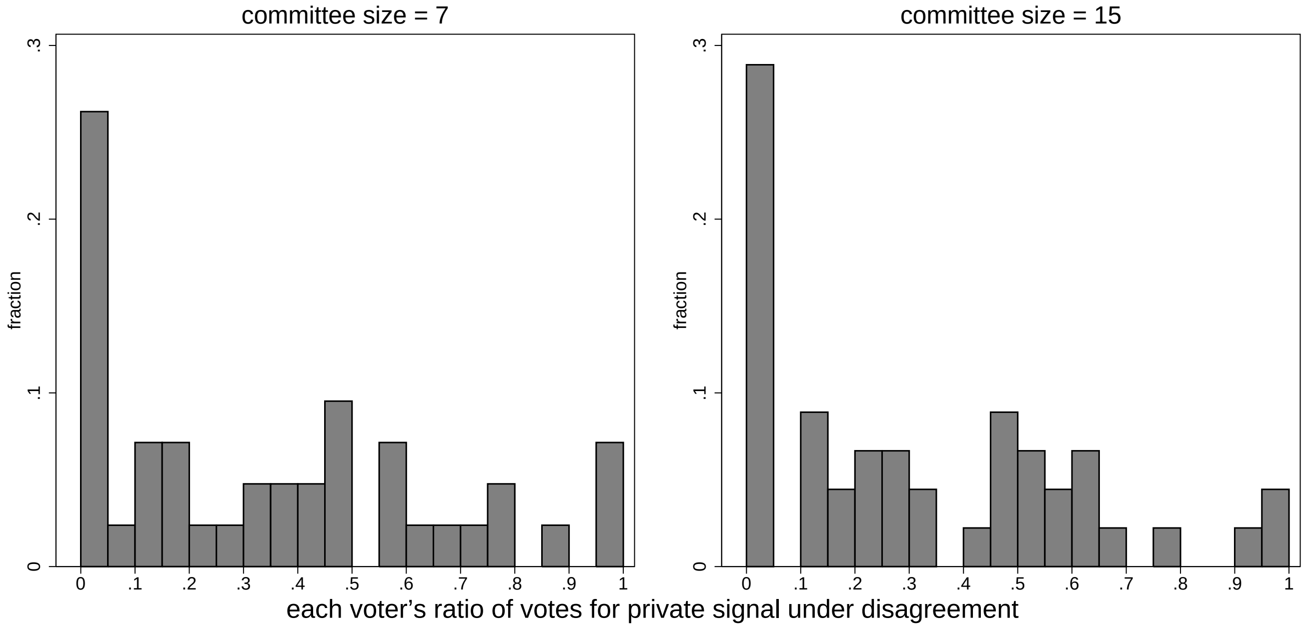

Figure 1: Distribution of voting behaviour with signals in disagreement

the efficiency of the committee decisions in the treatments with expert information and that in the treatments without expert information.

5.1 Voter choices with expert information

Let us first examine voting behaviour in the game with expert information. On Table 2 we can observe immediately that, when the private and public signals disagree, the subjects voted against their private signals much more often than they would in the efficiency improving symmetric mixed and asymmetric pure equilibria.

As the informational advantage of the expert information over private information is not large (70% versus 65%), in the symmetric mixed equilibrium the agents should vote according to the private signal most of the time when the signals disagree (93.8% in the seven-person and 97.5% in the fifteen-person committees, respectively). Also, from Proposition 6 only one agent should be obedient to the expert in the asymmetric pure equilibrium for both seven- and fifteen-person voting games, which implies the frequency of voting for the private signal of 85.7% and 93.3%, respectively.

In the laboratory, by contrast, when the two signals disagreed the subjects voted against their private signal in favour of the expert signal for the majority of the time, in both the seven-person and fifteen-person committees. The frequency of following their private signal was only 35.1% in the seven-person committees and 32.2% in the fifteen-person committees. This, together with the high frequency of voting according to agreeing signals which is close to 100%, implies a significant overall tendency to follow expert information both individually and collectively.

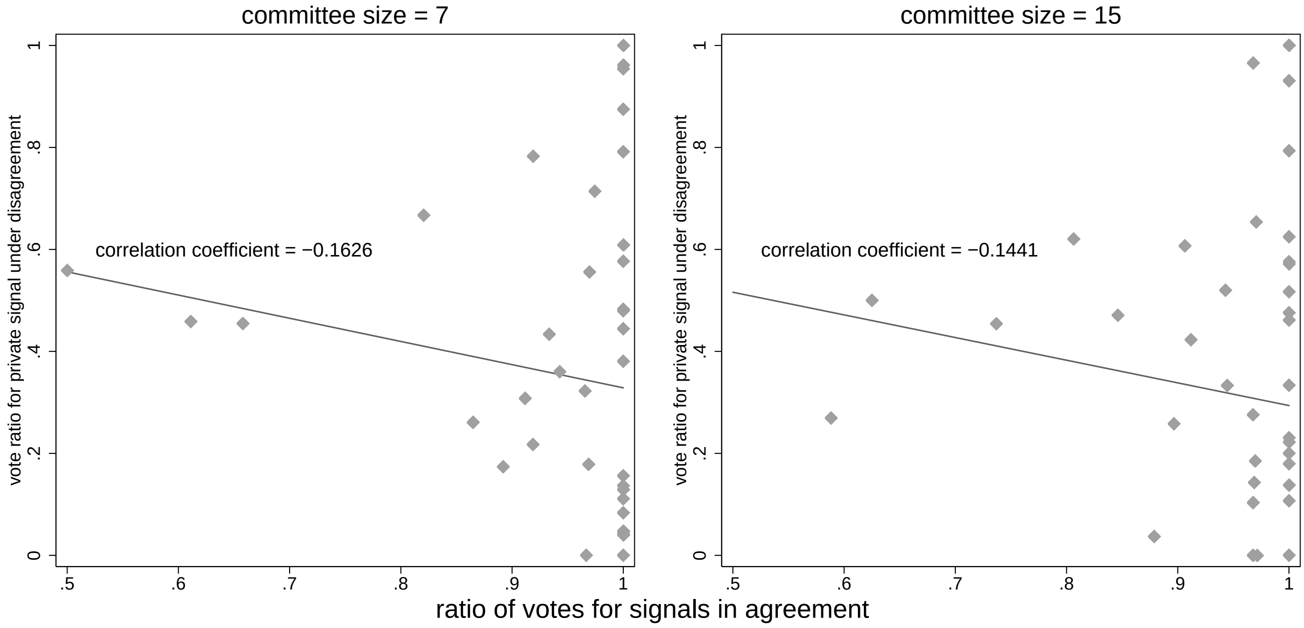

Figure 2: Voting behaviour with signals in agreement and disagreement

Before discussing the influence of expert information on the voting outcome, let us look at the heterogeneity and change in the subjects' voting behaviour within sessions. According to Figure 1, when the two signals disagreed, the highest fraction of the subjects (11 out of 42 in seven-person committees; 13 out of 45 in fifteen-person committees) voted against the private signal always, or almost always ($b < 5\%$, where b is each subject's the frequency of voting for the private signal when the signals disagree). Apart from those extreme "followers" of expert information, the subjects' behaviour in terms of b is relatively dispersed, while the density is still somewhat higher towards the left. At the other extreme there were some subjects who consistently followed private information. Therefore there was significant subject heterogeneity, and the low overall frequency of following the private signal as documented in Table 2 was largely driven by the extreme "followers".

Meanwhile, we do not observe comparable heterogeneity in our subjects' behaviour only when their signals agreed. Figure 2 indicates that most subjects voted according to signals in agreement most of the time, and moreover, across the subjects we find no systematic link between their behaviour when the signals agreed and when they disagreed. That is, while there is a significant variation in voting behaviour with signals in disagreement, even among the subjects who voted for the signals in agreement almost always (> 95%). In what follows we focus primarily on voting behaviour when the signals disagreed.

Figure 3 depicts the evolution of voting behaviour over periods of disagreement, where based on Figure 1 the subjects are divided into four behavioural types (with the bin width of 25%) according to b, how often they followed the private signal when the signals disagreed. The number of subjects who belong to each category is in parentheses the legend of Figure 3. For example, in the seven-person (fifteen-person) committee treatment, 19 out of 42 (22 out of 45) subjects voted for the private signal under disagreement less than 25% of the time. We computed the ratio of agents who followed the private signal for each of the four types, according to the order of occurrences of receiving signals that disagreed.[17] The thickness of the lines corresponds to the relative size of each quartile. Note that although the graphs are drawn over 25 periods, not every subject had 25 (or more) occurrences of disagreement since all signals were generated randomly and independently. In the seven-person committee treatment all subjects had 19 or more occurrences of disagreement, and in the fifteen-person committee treatment all subjects had 22 or more. The shaded areas indicate that not all subjects are included in computing the average voting behaviour under disagreement.

An interesting feature we observe in Figure 3 is that most subjects followed the public signal for the first few occurrences of disagreement. However, soon afterwards different types exhibited different voting patterns. In particular, the "unyielding" type of agents, who followed the private signal most often ($> 75\%$), quickly developed this distinct characteristic. It is as if there were a small number of subjects who "learnt" to ignore the public signal, in the face of the vast majority of the others already following it. At the other end, the behavioural pattern of the "obedient" type of agents, who followed the private signal least often ($\leq 25\%$), was relatively consistent across the occurrences of disagreement. The subjects who were in-between (frequency of voting for the private signal between 25% and 75%) started with voting for the public signal more often in the first few occurrences of disagreement but thereafter we do not observe a clear change in their voting behaviour over time. Overall, Figure 3 highlights the emergence of marked heterogeneity in voting behaviour in relatively early occurrences of disagreement. More importantly, Figure 3 does not show any clear sign of convergence to the strategies in the efficient asymmetric pure equilibrium identified earlier in Proposition 6.

Figure 3 also suggests that most subjects changed the way they responded to disagreement as if they randomized. In order to see what potentially influenced voting behaviour while taking into account significant individual heterogeneity as observed earlier, we ran random effects probit regressions for the rounds where the two signals disagreed. Table 3 shows that the subjects were more likely to vote for the public signal (and against their own private signal) when the public signal was correct (and the private signals was incorrect) in the previous occurrence of disagreement. Some subjects seem to have linked their choice to the observational accuracy of the expert signal, at least to some extent.

[17] Thus the subjects had the first (second, third, etc.) occurrence of disagreement in different periods of the session.

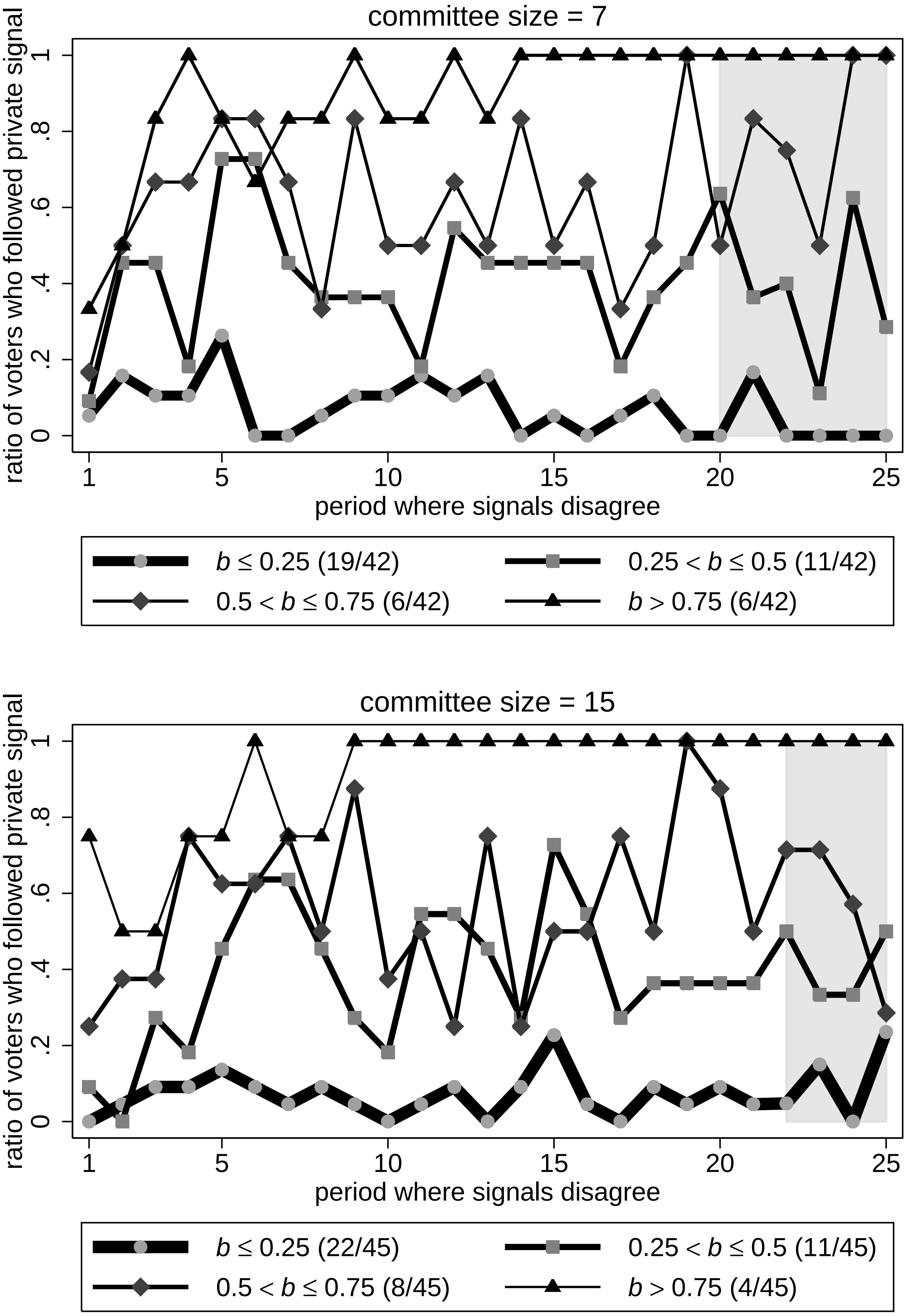

Figure 3: Change in average voting behaviour under disagreement for each agent type: $b =$ individual frequency of voting for private signal when signals disagreed

Table 3: Random effects probit: dependent variable = 1 if voted for private signal under disagreement

	7-person comm. (1032 obs.)		15-person comm. (1173 obs.)	
Period of disagreement	-0.0066	-0.0112	0.0125**	0.0168**
	(0.0067)	(0.0095)	(0.0059)	(0.0083)
Expert was correct in last disag. period	-0.2342**	-0.3595*	-0.5165***	-0.3885*
	(0.1009)	(0.2112)	(0.0960)	(0.1987)
Period of disagreement ×		0.0092		-0.0085
Expert was correct in last disag. period		(0.0135)		(0.0116)
Constant	-0.3557	-0.2986	-0.7486***	-0.8117***
	(0.2355)	(0.25045)	(0.2439)	(0.2586)
Log likelihood	-483.7402	-483.5117	-533.0635	-532.7938

Note: Standard errors in parentheses.

*** significant at 1% level; ** significant at 5% level; * significant at 10% level

5.2 Committee decisions with expert information

Let us now consider the majority decisions of the committees in relation to the presence of the public signal, which are summarized in Table 4. A striking feature for both treatments is that the decisions followed the expert information most of the time (97.8% for the seven-person committees and 100% for the fifteen-person committees), while the predictions for the two efficient equilibria suggest only 67-72%. Moreover, the decisions in the laboratory were much more likely to have margins of two or more than the predictions. Also, when for any decision that had a margin of two or more, the decision followed expert information. Those features are again far from the predictions of the efficient equilibria (see the last two rows of Table 4). If anything, as we will discuss shortly, the majority decisions exhibit key aspects of the hybrid obedient equilibrim we saw earlier.

5.3 Relation to equilibrium predictions

In Section 3 we considered three responsive equilibria of interest, namely the symmetric mixed, asymmetric pure, and obedient equilibria. Our subjects' voting choices and committee decisions exhibit some essential properties of the hybrid obedient equilibrium, where a supermajority ($(n+1)/2+1$ or more agents) vote according to the expert signal and the other agents' strategies are arbitrary. The indeterminacy of the minority agents' strategies makes it difficult to establish a solid link between the prediction and the data, but in what follows we argue that the subjects' behaviour in our data is best construed as that in the hybrid obedient equilibrium.

First, as we have seen in Table 4, the committee decisions followed the expert signal most of the time (97.8% for seven-person committees and 100% for fifteen-person committees) as in the obedient equilibria where the decision follows the expert signal with probability 1. In the other efficient equilibria we saw, this rate ranges from

Table 4: Majority decisions by committees with expert information

	7-person comm.			15-person comm.		
	treatment with	efficient equilibrium		treatment with	efficient equilibrium	
	expert (360 obs.)	sym.	asym.	expert (180 obs.)	sym.	asym.
Decision coincided with public signal	0.9778	0.6654	0.7237	1	0.6731	0.7023
Decisions made with margin ≥ 2	0.8583	0.5958	0.6000	1	0.7993	0.8033
of which followed public signal	1	0.6612	0.8143	1	0.6789	0.7396

67% to 72% for both treatments. The difference in frequency between the predictions from the two efficient equilibria and from the data is statistically significant.[18]

Second, again from Table 4, most decisions were made with the margin of two or more votes (85.8% of the time for seven-person committees and 100% for fifteen-person committees), which is an essential feature of the hybrid obedient equilibrium where no voter should be pivotal. The predicted frequency of the majority decisions having the margin of two or more in the efficient equilibria is about 60% for seven-person committees and 80% for fifteen-person committees.

Third, more importantly, most (by the seven-person committees) or all (by the fifteen-person committees) decisions made with the margin of two or more followed the expert signal, while in the efficient equilibria such decisions do not need to follow the expert signal (66-81%: see the last row of Table 4). From the subjects' perspective, it might well be that, having looked at the feedback every period, they perceived themselves as playing an obedient equilibrium in the sense that they anticipated that the decision would (almost) always follow the expert signal, and moreover they would not be able to influence the outcome as they would not be pivotal.

Fourth, from the viewpoint of individual voting choices, the marked heterogeneity makes symmetric strategies less plausible (Figures 1 and 3). Also, while the asymmetric pure strategy equilibrium requires only one agent to follow the expert in every period, there were on average more (1.8 subjects in the seven-person committees and 4.3 in the fifteen-person committees) who followed the expert signal more than 95% of the time. Combined with the fact that the other subjects also frequently voted for the expert signal in the face of disagreement, the profiles of voting choices seem much closer to those in the hybrid obedient equilibrium. Indeed, individual voting choices are largely consistent with its prediction, although it must be stressed that the arbitrariness of the equilibrium voting behaviour of a minority makes it difficult to relate the equilibrium and the data precisely.

Finally, Figure 3 shows no clear sign of "convergence" to either the efficient symmetric mixed or asymmetric pure equilibria. If anything, although the randomness of the combination of the two signals makes it very difficult to observe a long-run trend in the laboratory, from our data the voting pattern seems to have stabilized after several

[18]The p-value for the binomial test is 0.0000 for each efficient equilibrium with each committee size.

Table 5: Voting behaviour in committees without expert information

		7-person committees		15-person committees	
		treatment without expert (2520 obs.)	equilibrium	treatment without expert (2700 obs.)	equilibrium
vote for private signal	overall	0.8472	1	0.9141	1
	first 30	0.8505		0.9111	
	last 30	0.8437		0.9170	

occurrences of disagreement, in the manner closest to the hybrid obedient equilibrium as we have just discussed.

If we accept that an equilibrium was played (or approximated) and that the one played was the hybrid obedient equilibrium, then it implies that the subjects selected a less efficient equilibrium. Note that the efficient equilibria in our model may require substantive coordination among the agents, especially in the presence of underlying uncertainty in the state and two signals. The apparent simplicity of the obedient equilibrium might be the reason why it may have been chosen despite its inefficiency.[19]

Another possibility is that the subjects may not have been playing any equilibrium strategies and some or many were following the expert information out of “irrationality”. Even if this was the case, however, the fact that the obedient outcome with a supermajority is in equilibrium must have made it “robust” than otherwise, since even rational players could not do effectively anything to improve the efficiency.

5.4 Efficiency comparison

Since the committee decisions mostly followed the expert signal, their efficiency is almost (in the case of fifteen person committees, completely) identical to that of the expert signal. If we posit that the subjects play the hybrid obedient equilibrium and that those in the treatments without expert information play the informative equilibrium by following each one’s private signal, then from (8), in expectation we should observe the efficiency loss of $P_C(0.65, 7) - 0.7 = 0.1002$ (14.3% reduction) for the seven-person committees and $P_C(0.65, 15) - 0.7 = 0.1868$ (26.7% reduction) due to the *presence* of expert information.

In the laboratory, the subjects in the treatments without expert information did not necessarily play according to the equilibrium prediction of informative voting (Table 5). The deviation is more pronounced in the seven-person committees than in the fifteen-person committees, which is probably because subjects tended to deviate after observing the majority decision being wrong and indeed by construction (conditional

[19]In the literature on voting experiments, it is common to consider quantal response equilibrium (QRE; McKelvey and Palfrey, 1995) to see whether the experimental data on subjects’ actions can be interpreted as deviation from a particular equilibrium prediction of interest. See Appendix II for further discussion on QRE.

Table 6: Observed efficiency

	7-person comm. (180 obs. each)		15-person comm. (360 obs. each)	
	w/o expert	with expert	w/o expert	with expert
Observed efficiency	0.7000	0.7389	0.8278	0.6778
Fisher's exact test for difference	not significant ($p = 0.2809$)		significant ($p = 0.0000$)	
Observed efficiency of expert information	n/a	0.7222	n/a	0.6778
Hypoth. efficiency with individually informative voting	0.7972	0.8195	0.8778	0.8667

on informative voting) the decisions are less likely to be correct in the seven-person committees (see Appendix III for details). Note that, from each individual's perspective, one private signal is less informative of the true state than a pair of private and public signals in agreement. We have observed in Table 2 that the proportion of votes for the agreeing signals was about 95% in both seven-person and fifteen-person committees, which is higher than the proportion of votes for the public signal when expert information is absent. This is consistent with, for example, the result from Morton and Tyran (2011) who found that the more accurate the information subjects receive, the more likely it is that they vote according to the information.

Since informative voting achieves the highest efficiency in the voting game without expert information, any deviation from the equilibrium strategy leads to efficiency loss. The first row on Table 6 records the observed (ex post) efficiency in the four treatments. We can see that the efficiency of the decisions by the seven-person committees without expert information was merely 70.0%, while if they every member voted individually informatively following the equilibrium strategy, given the actual signal realizations in the treatment, they could achieve 79.7%. Meanwhile the seven-person committees with expert information achieved 73.9%, even though they could have achieved higher efficiency (82.0%) had they adopted individually informative voting. [20] While the precise comparison of efficiency between the seven-person committees with and without expert information is difficult due to different signal realizations in each treatment, the difference in the observed efficiency is not statistically significant.

The last two columns of Table 6 give us a somewhat clearer picture. In the fifteen-person committees without expert information, since the agents did not deviate much from the equilibrium strategy of informative voting, the efficiency loss compared to the hypothetical informative voting was small (82.8% vs. 87.8%). In the fifteen-person committees with expert information, since all decisions followed the expert information, the efficiency was exactly the same as that of the expert signals, which was only 67.8%. Although the exact comparison is not possible due to different signal realizations in each treatment, the reduction in efficiency in the treatment with expert information is

[20]Recall that individually informative voting is not an equilibrium strategy in the presence of expert information. Here we record the hypothetical efficiencies for both seven-person and fifteen-person committees in order to represent the quality of the realized private signals in each treatment.

large (82.8% $\rightarrow$ 67.8%, 22.1% reduction) and statistically significant.

6 Conclusions

This paper has studied the effects of a public signal on voting behaviour in committees of common interest. In the first part of the paper, we have demonstrated that the presence of publicly observed expert information changes the structure of voting equilibria substantially. In particular, individually informative voting is no longer an equilibrium when the precision of the public signal is better than each agent's individual signal, as in expert opinions presented to the entire committee. If the expert information is not too accurate, there are three informative equilibria of interest, namely i) the symmetric mixed strategy equilibrium where each member randomizes between following the private and public signals should they disagree; ii) the asymmetric pure strategy equilibrium where a certain number of members always follow the public signals while the others always follow the private signal; and iii) a class of equilibria where the committee's majority decision always follows the expert information. When the expert information is not too accurate, i) and ii) are more efficient but iii) can be less efficient than the sincere voting equilibrium without expert information. If the expert information is very accurate, then the only informative equilibrium involves obedient voting, whereby every agent follows expert information, and this equilibrium is indeed efficient.

In the second part, we have reported on the laboratory experiment we conducted to see how human subjects react to expert information. In particular we set the parameter values in such a way that the efficiency of the obedient equilibria is lower than what the agents could have achieved in the sincere voting equilibrium without expert information. We found that the subjects followed expert information so frequently that most of the time the committee decisions were the same as what the expert signal indicated. This is in sharp contrast to the predictions from the efficient equilibria, where only a small number of agents should (in expectation) follow the expert signal and as a result the committee decision and expert signal may not necessarily coincide. We also found that the subjects' behaviour was highly heterogeneous. Moreover the heterogeneity was persistent over many periods and there was no clear sign of convergence to an efficient equilibrium. Given the outcome and the heterogeneity in voting behaviour among the subjects, we have argued that their choices can be best interpreted as those in a *hybrid obedient equilibrium*, where a supermajority follow expert information and the rest vote arbitrarily.

We have then contrasted the results to those from the control treatments where the subjects received private signals only. We found that the efficiency without expert information was significantly higher than the efficiency with expert information for fifteen-person committees. One interpretation of this result is that, the otherwise efficiency improving provision of expert information actually reduced efficiency, by creating an inefficient equilibrium that is simple to play compared to the efficient equilibria. The difference in efficiency was not significant for seven-person committees, largely due to the agents' frequent non-equilibrium behaviour in the treatment without expert information, which reduced the efficiency and made it close to the efficiency of the committee decisions in the treatment with expert information.

Finally, this paper offers a potentially relevant "policy" implication. The optimality of the asymmetric pure strategy equilibrium suggests that it may be desirable for the expert to speak only to a subset of the members of a committee, unless his expertise q is overwhelmingly high. The number of members he should speak to is m^*, as explicitly computed for Proposition 6. In this case, the outcome of the equilibrium where m^* members follow the expert and the rest follow the private signal is identical to the outcome of the asymmetric pure strategy equilibrium we have seen earlier, but this form of selective information revelation rules out equilibria that are less efficient, such as the symmetric pure strategy equilibrium and the obedient equilibrium. Alternatively, if an expert is heard by all members, there should be some coordination device such as role assignment in place to make sure that the expert will not have excessive influence on committee members. The results from our experiment suggest that it may not be adequate to study an efficient equilibrium especially when it requires subtle coordination among many players, as is often the case in decision making by voting under uncertainty.

7 Appendix I: Proofs

7.1 Proposition 1

Proof. Consider agent i's strategy in the putative equilibrium where all the other agents adopt the individually informative strategy. He computes the difference in the expected payoff between voting for A and B, conditional on his private and public signals, in the event where he is pivotal. The payoff difference is given by

$$\begin{aligned} w(\sigma_i, \sigma_E) &\equiv E[u_i(A,s) - u_i(B,s) | Piv(v_{-i}), \sigma_i, \sigma_E] \mathrm{Pr}[Piv(v_{-i}), \sigma_i, \sigma_E] \\ &= \frac{1}{2}\mathrm{Pr}[\sigma_E | s = A]\mathrm{Pr}[\sigma_i | s = A]\mathrm{Pr}[Piv(v_{-i}) | s = A] \\ &- \frac{1}{2}\mathrm{Pr}[\sigma_E | s = B]\mathrm{Pr}[\sigma_i | s = B]\mathrm{Pr}[Piv(v_{-i}) | s = B], \end{aligned} \tag{3}$$

where the equality follows from the independence of the signals in individually informative voting. Without loss of generality, let us assume $\sigma_i = B$ and $\sigma_E = A$. From (3) we have

$$
\begin{aligned}
w(B,A) &= \frac{1}{2}\left(q(1-p)\frac{(n-1)!}{\left[\left(\frac{n-1}{2}\right)!\right]^2} p^{\frac{n-1}{2}}(1-p)^{\frac{n-1}{2}}\right) \\
&\quad - \frac{1}{2}\left((1-q)p\frac{(n-1)!}{\left[\left(\frac{n-1}{2}\right)!\right]^2} p^{\frac{n-1}{2}}(1-p)^{\frac{n-1}{2}}\right) \\
&= \frac{1}{2}(q-p)\frac{(n-1)!}{\left[\left(\frac{n-1}{2}\right)!\right]^2} p^{\frac{n-1}{2}}(1-p)^{\frac{n-1}{2}} > 0.
\end{aligned}
$$

The inequality holds since $q > p$. This implies that agent i votes for A despite her private signal B. Thus individually informative voting is not a Bayesian Nash equilibrium. □

7.2 Proposition 3

Before deriving the equilibrium, it is useful to note that the mixed strategy equilibrium takes a "hybrid" form, where mixing occurs only when the private and public signals disagree.

Lemma 1. *Suppose there exists a symmetric Bayesian Nash equilibrium in mixed strategies. In such an equilibrium, any agent whose private signal coincides with the public signal votes according to the signals with probability* 1.

Proof. Without loss of generality, let us assume $\sigma_E = A$ to prove the lemma.

Define

$$
\begin{aligned}
F(A) \equiv \Pr[Piv(v_{-i})|s=A] &= \sum_{k=0}^{n-1} \sum_{j=0}^{\min\left(k,\frac{n-1}{2}\right)} \binom{n-1}{k} p^k (1-p)^{n-1-k} \\
&\quad \times \binom{k}{j} \alpha^j (1-\alpha)^{k-j} \binom{n-1-k}{\frac{n-1}{2}-j} (1-\beta)^{\frac{n-1}{2}-j} \beta^{\frac{n-1}{2}-k+j} \qquad (4)
\end{aligned}
$$

and

$$
\begin{aligned}
F(B) \equiv \Pr[Piv(v_{-i})|s=B] &= \sum_{k=0}^{n-1} \sum_{j=0}^{\min\left(k,\frac{n-1}{2}\right)} \binom{n-1}{k} p^k (1-p)^{n-1-k} \\
&\quad \times \binom{k}{j} \beta^j (1-\beta)^{k-j} \binom{n-1-k}{\frac{n-1}{2}-j} (1-\alpha)^{\frac{n-1}{2}-j} \alpha^{\frac{n-1}{2}-k+j}. \qquad (5)
\end{aligned}
$$

Using $F(A)$ and $F(B)$, we rewrite

$$
\begin{aligned}
w(A,A) &= \frac{1}{2}\left[qpF(A) - (1-q)(1-p)F(B)\right] \qquad (6) \\
w(B,A) &= \frac{1}{2}\left[q(1-p)F(A) - (1-q)pF(B)\right]. \qquad (7)
\end{aligned}
$$

Note that (6) and (7) incorporate each agent's Bayesian updating on the state and the private signals other agents may have received, conditional on his own signal and the public signal.

In order to have fully mixing equilibrium, namely $\alpha^* \in (0,1)$ and $\beta^* \in (0,1)$, we must have $w(A,A) = 0$ and $w(B,A) = 0$ simultaneously for indifference. In what follows, we show that $w(A,A) > 0$ for any α and β, which implies in equilibrium we must have $\alpha^* = 1$ and if mixing occurs it must be only for β, that is, when the private and public signals disagree. Specifically, we show that $F(A) > F(B)$, which readily implies $w(A,A) > 0$ from (6).

From (6) and (7) we have $F(A) - F(B) > 0$ if

$$\begin{aligned}\alpha^j(1-\alpha)^{k-j}(1-\beta)^{\frac{n-1}{2}-j}\beta^{\frac{n-1}{2}-k+j} &> \beta^j(1-\beta)^{k-j}(1-\alpha)^{\frac{n-1}{2}-j}\alpha^{\frac{n-1}{2}-k+j}\\ &\Leftrightarrow \beta(1-\beta) > \alpha(1-\alpha)\\ &\Leftrightarrow (\alpha+\beta-1)(\alpha-\beta) > 0. \qquad (8)\end{aligned}$$

To see that (8) holds we will show that in equilibrium $\alpha^* + \beta^* - 1 > 0$ and $\alpha^* - \beta^* > 0$.

Let us first observe that $\alpha^* + \beta^* - 1 > 0$. The difference in the difference in payoffs between voting for A and B is given by

$$w(A,A) - w(B,A) = \frac{q(2p-1)}{2}F(A) + \frac{(1-q)(2p-1)}{2}F(B) > 0, \qquad (9)$$

since both terms in the right hand side are positive since $p, q > 1/2$. Thus, given $\sigma_E = A$, the equilibrium probability of voting for A when $\sigma_i = A$ must be strictly greater than that of voting for A when $\sigma_i = B$, which implies[21]

$$\alpha^* + \beta^* - 1 > 0. \qquad (10)$$

Second, let us show that $\alpha^* > \beta^*$. We assume instead that $\alpha^* \leq \beta^*$ in equilibrium and derives a contradiction. There is no hybrid equilibrium such that $\alpha^* \in (0,1)$ and $\beta^* = 1$, because from (8) and (10), $\alpha^* \leq \beta^*$ implies $F(A) \leq F(B)$ and we may have a fully mixed equilibrium, in which case $w(A,A) = w(B,A) = 0$. From (6) we have

$$w(A,A) = 0 \Rightarrow \frac{F(A)}{F(B)} = \frac{(1-q)(1-p)}{qp}, \qquad (11)$$

and from (7)

$$w(B,A) = 0 \Rightarrow \frac{F(A)}{F(B)} = \frac{(1-q)p}{q(1-p)}. \qquad (12)$$

We can see that (11) and (12) hold simultaneously if and only if $p = 1/2$, which is a

[21] See Lemma 1 in Wit (1998) for a similar argument.

contradiction, since $p \in (1/2, 1]$. Thus we conclude that $\alpha^* > \beta^*$ in any mixed strategy equilibrium equilibrium.

Combining $\alpha^* > \beta^*$ and (10), we can see that (8) holds. Thus we have $F(A)-F(B) > 0$ and $w(A, A) > 0$, which implies any mixed strategy equilibrium has to have a hybrid form, such that $\alpha^* = 1$. □

Lemma 1 is not surprising, because when both signals coincide they would jointly be very informative about the actual state. The non-trivial part of the lemma is that this intuition holds regardless of the mixing probability when the signals disagree. Thanks to the lemma we can focus on mixing when the private and public signals disagree.

Proof of Proposition 3. From Lemma 1 any mixed strategy equilibrium involves $v_i(A, A) = v_i(B, B) = 1$ and $v_i(A, B) = v_i(B, A) = \beta \in (0, 1)$ for any $i \in N$. When the state and the public signal match, the probability of each individual voting correctly for the state is given by

$$r_a \equiv p + (1-p)(1-\beta), \tag{13}$$

and when the state and the public signal disagree, the probability of each individual voting correctly is

$$r_b \equiv (1-p) \times 0 + p\beta = p\beta. \tag{14}$$

To have $\beta^* \in (0, 1)$, we need any agent to be indifference when the two signals disagree:

$$w(B, A) = q(1-p)\binom{n-1}{\frac{n-1}{2}} r_a^{\frac{n-1}{2}} (1-r_a)^{\frac{n-1}{2}} - (1-q)p\binom{n-1}{\frac{n-1}{2}} r_b^{\frac{n-1}{2}} (1-r_b)^{\frac{n-1}{2}} = 0 \tag{15}$$

$$\Rightarrow \frac{1-p\beta}{1-\beta(1-p)} = \left(\frac{q}{1-q}\right)^{\frac{2}{n-1}} \left(\frac{1-p}{p}\right)^{\frac{n+1}{n-1}} \tag{16}$$

$$\Rightarrow \beta^* = \frac{1-A(p, q, n)}{p - A(p, q, n)(1-p)}, \tag{17}$$

such that $A(p, q, n) = \left(\frac{q}{1-q}\right)^{\frac{2}{n-1}} \left(\frac{1-p}{p}\right)^{\frac{n+1}{n-1}}$. Thus when $\beta^* \in (0, 1)$ we obtain a mixed strategy equilibrium of the hybrid form ($\alpha^* = 1$).

Finally, solving $\beta^* = 0$ for q, we see that $\beta^* \in (0, 1)$ if and only if $q \in \left(p, \frac{\left(\frac{p}{1-p}\right)^{\frac{n+1}{2}}}{1+\left(\frac{p}{1-p}\right)^{\frac{n+1}{2}}}\right)$. The uniqueness follows from the fact that the left hand side of (16) is strictly decreasing in β. □

7.3 Proposition 4

Proof. In what follows we will find $\alpha = v_i(A, A) = v_i(B, B)$ and $\beta = v_i(B, A) = v_i(A, B)$ that maximize the probability of the majority outcome matching the correct state. Conditional on the state $s = A$ and $\sigma_E = A$, let the ex ante probability of each agent voting for A be, from (13), $r_a \equiv p\alpha + (1-p)(1-\beta)$. Also from (14), conditional on the state $s = A$ and $\sigma_E = B$, let the probability of each agent voting for A be $r_b \equiv p\beta + (1-p)(1-\alpha)$. Using r_a and r_b, the ex ante probability $P(\alpha, \beta)$ that the majority decision matches the state can be written as

$$\begin{aligned}
P(\alpha, \beta) =& \Pr[M = s|s] = \Pr[M = A|s = A]P[A] + \Pr[M = B|s = B]P[B] \\
=& \Pr[M = A|s = A]\frac{1}{2} + \Pr[M = B|s = B]\frac{1}{2} = \Pr[M = A|s = A] \\
=& \Pr[\sigma_E = A|s = A]\Pr[M = A, \sigma_E = A|s = A] \\
&+ \Pr[\sigma_E = B|s = A]\Pr[M = A, \sigma_E = B|s = A] \\
=& q \sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} r_A^k (1 - r_A)^{n-k} + (1 - q) \sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} r_B^k (1 - r_B)^{n-k}. \qquad (18)
\end{aligned}$$

Note that for

$$g(x) \equiv \sum_{k=\frac{n+1}{2}}^{n} \binom{n}{k} x^k (1 - x)^{n-k}$$

we have

$$\frac{dg(x)}{dx} = n\binom{n-1}{\frac{n-1}{2}} (x(1 - x))^{\frac{n-1}{2}}.$$

Partially differentiating (18) with respect to α and β, we obtain

$$\begin{aligned}
\frac{\partial P(\alpha, \beta)}{\partial \alpha} =& npq\binom{n-1}{\frac{n-1}{2}} (r_a(1 - r_a))^{\frac{n-1}{2}} \\
&- n(1 - p)(1 - q)\binom{n-1}{\frac{n-1}{2}} (r_b(1 - r_b))^{\frac{n-1}{2}} \qquad (19)
\end{aligned}$$

and

$$\begin{aligned}
\frac{\partial P(\alpha, \beta)}{\partial \beta} =& -(1 - p)nq\binom{n-1}{\frac{n-1}{2}} (r_a(1 - r_a))^{\frac{n-1}{2}} \\
&+ pn(1 - q)\binom{n-1}{\frac{n-1}{2}} (r_b(1 - r_b))^{\frac{n-1}{2}}. \qquad (20)
\end{aligned}$$

From (20), taking the first order condition with respect β we have

$$\frac{\partial P(\alpha, \beta)}{\partial \beta} = 0 \Leftrightarrow \left(\frac{r_b(1 - r_b)}{r_a(1 - r_a)}\right)^{\frac{n-1}{2}} = \frac{q(1 - p)}{(1 - q)p}. \qquad (21)$$

If (21) holds, then the derivative with respect to α, (19), is strictly positive for any $\alpha \in [0, 1]$ since

$$\begin{aligned}\frac{\partial P(\alpha,\beta)}{\partial \alpha} > 0 &\Leftrightarrow \frac{qp}{(1-q)(1-p)} > \left(\frac{r_b(1-r_b)}{r_a(1-r_a)}\right)^{\frac{n-1}{2}} \\ &\Leftrightarrow \frac{qp}{(1-q)(1-p)} > \frac{q(1-p)}{(1-q)p} \\ &\Leftrightarrow p > \frac{1}{2}.\end{aligned}$$

Therefore we have a unique corner solution for α, namely $\alpha = 1$, which coincides with the equilibrium α^* in the hybrid mixed strategy identified in Proposition 3. Note that the first order condition (20) and the indifference condition for the mixed strategy equilibrium (15) also coincide. Thus $\beta = \beta^*$ satisfies the first order condition.

It remains to show that the second order condition for the maximization with respect to β is satisfied. Since $P(\alpha,\beta)$ is a polynomial it suffices to show that

$$\begin{aligned}\frac{\partial^2 P(\alpha,\beta)}{\partial \beta^2} < 0 \Rightarrow &-(1-p)nq\binom{n-1}{\frac{n-1}{2}}\left(r_a(1-r_a)\right)^{\frac{n-3}{2}}\left(1-p-2\beta(1-p)^2\right) \\ &< pn(1-q)\binom{n-1}{\frac{n-1}{2}}\left(r_b(1-r_b)\right)^{\frac{n-3}{2}}\left(p-2\beta p^2\right). \qquad (22)\end{aligned}$$

At $\beta = \beta^*$, (22) reduces to

$$(1-p\beta)(1-2(1-p)\beta) > (1-2p\beta)(1-(1-p)\beta),$$

which holds since $p > \frac{1}{2}$. Since $P(\alpha, \beta)$ is a continuously differentiable function on a closed interval, the local maximum at $\{\alpha, \beta\} = \{1, \beta^*\}$ is also the global maximum. □

7.4 Proposition 6

Proof. Let us consider first the m obedient agents, assuming the rest always vote according to the private signal. In order for them to ignore their private signal when the two signals disagree, we have to have $w^{\text{obedient}}(B, A) \geq 0$ for those agents. If such an agent is pivotal given the strategy profile, among the $n - m$ individually informative agents, $(n-1)/2$ of them must have received the private signal that disagrees with the public signal, while $(n-1)/2 - (m-1)$ of them must have received the private signal that agrees with the public signal. Therefore, for the obedient agent not to deviate when the two signals he has received disagree, it has to be that

$$\begin{aligned} w^{\text{obedient}}(B,A) \geq 0 \Rightarrow\ & q(1-p)\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}-(m-1)}(1-p)^{\frac{n-1}{2}} \\ & - (1-q)p\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}}(1-p)^{\frac{n-1}{2}-(m-1)} \geq 0 \\ & \Rightarrow q(1-p)p^{-(m-1)} \geq (1-q)p(1-p)^{-(m-1)} \\ & \Rightarrow m \leq \frac{\ln[q]-\ln[1-q]}{\ln[p]-\ln[1-p]}. \end{aligned} \tag{23}$$

In other words, in order for the obedient agent not to deviate, the number of obedient agents cannot be too large. Given (23), if the public and private signals agree, the obedient agent votes according to the signals becauserespresented

$$\begin{aligned} w^{\text{obedient}}(A,A) =\ & qp\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}-(m-1)}(1-p)^{\frac{n-1}{2}} \\ & - (1-q)(1-p)\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}}(1-p)^{\frac{n-1}{2}-(m-1)} \\ & > q(1-p)\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}-(m-1)}(1-p)^{\frac{n-1}{2}} \\ & - (1-q)p\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}}(1-p)^{\frac{n-1}{2}-(m-1)} \\ & = w^{\text{obedient}}(B,A) \geq 0. \end{aligned}$$

The strict inequality follows from $w^{\text{obedient}}(B,A) \geq 0$ and $p > 1/2$.

Next, let us consider the $n-m$ individually informative agents who always follow their private signal regardless of the public signal. If an agent in this group is pivotal, it has to be that $(n-1)/2$ of them have received the private signal that disagrees with the public signal, while $(n-1)/2-m$ of them have received the private signal that agrees with the public signal. Therefore, in order for the individually informative agent not to deviate when the two signals he has received disagree, it has to be that

$$\begin{aligned} w^{\text{ind. informative}}(B,A) < 0 \Rightarrow\ & q(1-p)\binom{n-m}{\frac{n-1}{2}} p^{\frac{n-1}{2}-m}(1-p)^{\frac{n-1}{2}} \\ & - (1-q)p\binom{n-m}{\frac{n-1}{2}} p^{\frac{n-1}{2}}(1-p)^{\frac{n-1}{2}-m} < 0 \\ & \Rightarrow q(1-p)p^{-m} < (1-q)p(1-p)^{-m} \\ & \Rightarrow m > \frac{\ln[q]-\ln[1-q]}{\ln[p]-\ln[1-p]} - 1. \end{aligned} \tag{24}$$

In other words, in order for the individually informative agent not to deviate, the number of obedient agents cannot be too small. Given (24), if the public and private signals agree, the agent indeed votes according to the signals because

$$\begin{aligned} w^{\text{ind. informative}}(A,A) &= (1-q)(1-p)\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}-(m-1)}(1-p)^{\frac{n-1}{2}} \\ &\quad - qp\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}}(1-p)^{\frac{n-1}{2}-(m-1)} \\ &< q(1-p)\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}-(m-1)}(1-p)^{\frac{n-1}{2}} \\ &\quad - (1-q)p\binom{n-(m-1)}{\frac{n-1}{2}} p^{\frac{n-1}{2}}(1-p)^{\frac{n-1}{2}-(m-1)} \\ &= w^{\text{ind. informative}}(B,A) < 0. \end{aligned}$$

The strict inequality follows from $w^{\text{ind. informative}}(B,A) \geq 0$ and $p > 1/2$.

In equilibrium both (23) and (24) have to be satisfied, which gives the unique m^* in $\hat{M}$ as long as $m^* < (n+1)/2$. If $m^* = (n+1)/2$ then the majority decision always coincides with the public signal, and hence any $m \geq (n+1)/2$ in M is an equilibrium. Suppose $m^* > (n+1)/2$. In this case $m = (n+1)/2$ is also an equilibrium since none of the “individually informative” agents are pivotal and no “obedient” agent deviates as (23) is satisfied, which implies any $m \geq (n+1)/2$ in M is an equilibrium. □

7.5 Proposition 7

Proof. Nitzan and Paroush (1982) gave the optimal weighted majority rule with i) non-strategic sincere voting; ii) agents each of whom observes a private signal with different accuracy; and iii) no public signal. Let us consider the special case of their setup where the signal of one “expert” agent has the accuracy of q and those of $n-1$ “non-expert” agents have the same accuracy of $p \in (0,1)$, where $q > p$. In what follows we show that the optimal rule in their model and the asymmetric pure strategy equilibrium in $\hat{M}$ are isomorphic in terms of efficiency.

Theorem 1 in Nitzan and Paroush (1982) implies that, in the unique optimal majority rule, the expert has $\ln[q] - \ln[1-q]$ votes, while each non-expert agent has $\ln[p] - \ln[1-p]$ votes.[22] Equivalently, dividing the weights by $\ln[p] - \ln[1-p]$, the expert should have $\frac{\ln[q]-\ln[1-q]}{\ln[p]-\ln[1-p]}$ votes if every non-expert is to have one vote. Moreover, under this optimal rule, removing the votes of $\bar{m}$ randomly chosen non-experts ex ante does not affect the ex ante expected welfare, where $\bar{m}$ is defined as the largest integer that satisfies $m \leq \frac{\ln[q]-\ln[1-q]}{\ln[p]-\ln[1-p]}$ (Corollary 1 in Nitzan and Paroush, 1982). This is because the ex ante influence of their votes on the expected welfare is cancelled by the increased votes of the expert. It is straightforward to see that the same efficiency is implemented by the majority rule where ex ante the expert has $\bar{m}$ votes, each of $n - \bar{m}$ non-experts has one vote, and $\bar{m}$ non-experts have no vote. Clearly we have $\bar{m} = m^*$. Therefore m^*

[22]Here we allow non-integer votes and the majority decision is the alternative that received more votes.

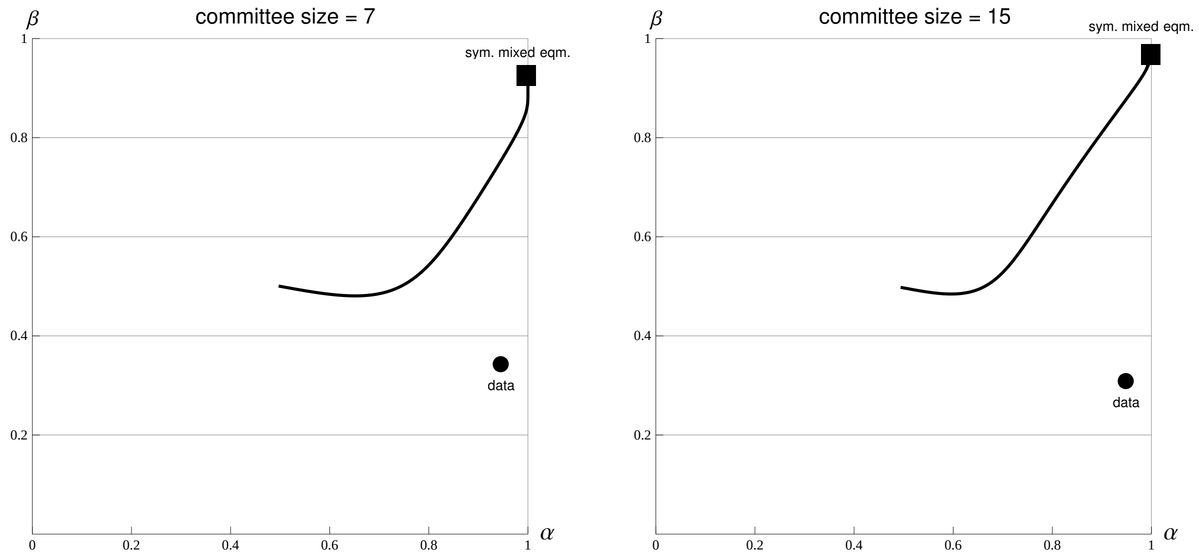

Figure 4: Data and logistic QRE predictions

uniquely maximizes the expected welfare in M.

Moreover, m^* in M is the unique maximizer of welfare in the set of entire strategy profiles Γ. To see this, note that Nitzan and Paroush (1982) allow $p < 1/2$ with sincere voting, which is equivalent to allowing agents to vote against their signal in our setting where $p > 1/2$. Also, uninformative voting by any agent clearly reduces efficiency relative to the optimal weights and thus cannot be part of the optimal rule. For any mixed strategy profiles, suppose that, without loss of generality, before observing the two signals, each agent individually decides which alternative to vote for, conditional on each combination of the two signals, according to his mixing probability. After these "interim decisions" but before the agents receive the signals, we can compute the expected welfare for each combination of their "interim decisions". The profiles of their "interim decisions" and their expected welfare coincide with those of the optimal rule only with probability less than 1. Hence the asymmetric pure strategy equilibrium with m^* achieves the highest ex ante expected welfare over the set of all strategy profiles Γ. □

8 Appendix II: Quantal response equilibrium

While unfortunately it is very difficult for the QRE model to generate quantitative predictions for asymmetric equilibria of games with incomplete information (such as ours), we can see whether subjects' aggregate behaviour can be systematically linked to the symmetric mixed equilibrium in Proposition 3, which is more efficient than the obedient equilibrium and the sincere voting equilibrium without public information. In this Appendix we argue that our data cannot be construed as systematic deviation from the symmetric mixed equilibrium.

Let us derive the logistic quantal response function for the rationality parameter λ, where $\lambda \to \infty$ corresponds to perfect rationality and the symmetric mixed equilibrium under consideration and $\lambda = 0$ corresponds to complete randomization (voting for either alternative with 50% regardless of the information). Let $\alpha = v_{-i}(A, A) = v_{-i}(B, B)$ and $\beta = v_{-i}(B, A) = v_{-i}(A, B)$ for any $-i \in \{1, 2, ..., i-1, i+1, ..., n\}$. That is, α is the probability that all agents except agent i vote according to the signals in agreement, and b is the probability that all agents except agent i vote according to the private signal when the signals disagree. Given that the expert signal is correct, the probability of each agent $-i$ voting for the correct state is $r_a \equiv p\alpha + (1-p)(1-\beta)$. Also, given that the expert signal is correct, the probability of each agent $-i$ voting for the correct state is $r_b \equiv p\beta + (1-p)(1-\alpha)$. Suppose these agents follow the mixed strategy as described in Proposition 3.

If agent i votes according to the signals in agreement, his expected payoff is given by

$$
\begin{aligned}
E[u_i^{AA}(\alpha, \beta)] &= \frac{pq}{pq + (1-p)(1-q)} G(n-1, (n+1)/2, r_a) \\
&+ \frac{(1-p)(1-q)}{pq + (1-p)(1-q)} G(n-1, (n+1)/2, r_b),
\end{aligned}
$$

where

$$
G(n, l, x) \equiv \sum_{k=l}^{n} \binom{n}{k} x^k (1-x)^{n-k}.
$$

If agent i votes against the signals in agreement, his expected payoff is given by

$$
\begin{aligned}
E[u_i^{AO}(\alpha, \beta)] &= \frac{pq}{pq + (1-p)(1-q)} G(n-1, (n+1)/2, r_a) \\
&+ \frac{(1-p)(1-q)}{pq + (1-p)(1-q)} G(n-1, (n+1)/2 - 1, r_b).
\end{aligned}
$$

If agent i votes according to the private signal when the private and public signals disagree, his expected payoff is given by

$$
\begin{aligned}
E[u_i^{DP}(\alpha, \beta)] &= \frac{q(1-p)}{q(1-p) + p(1-q)} G(n-1, (n+1)/2, r_a) \\
&+ \frac{p(1-q)}{q(1-p) + p(1-q)} G(n-1, (n+1)/2 - 1, r_b).
\end{aligned}
$$

If agent i votes according to the public signal when the private and public signals disagree, his expected payoff is given by

$$E[u_i^{DE}(\alpha,\beta)] = \frac{q(1-p)}{q(1-p)+p(1-q)}G(n-1,(n+1)/2-1,r_a) + \frac{p(1-q)}{q(1-p)+p(1-q)}G(n-1,(n+1)/2,r_b).$$

Hence we have

$$\alpha(\lambda) = \frac{exp(\lambda E[u_i^{AA}(\alpha,\beta)])}{exp(\lambda E[u_i^{AA}(\alpha,\beta)]) + exp(\lambda E[u_i^{AO}(\alpha,\beta)])}, \quad (25)$$

$$\beta(\lambda) = \frac{exp(\lambda E[u_i^{DP}(\alpha,\beta)])}{exp(\lambda E[u_i^{DP}(\alpha,\beta)]) + exp(\lambda E[u_i^{DE}(\alpha,\beta)])}. \quad (26)$$

The α and β that satisfy the system of equations (25) and (26) for $p = 0.65$, $q = 0.7$, and $n = 7, 15$ as in the experiment are plotted on Figure 4, where the square dots correspond to $\lambda \to \infty$ and thus the symmetric mixed equilibrium for each treatment. Clearly the data, represented by the circle dots, is further away from the QRE predictions.

In particular, with respect to the predictions, the likelihood of making an error when the signals agree is significantly different from when the signals disagree (as can also be seen in Table 2 and Figure 2). This is because, while the voting behaviour with signals in agreement is very close to the equilibrium prediction (voting for these signals with probability 1), the voting behaviour with signals in disagreement deviates substantially from that in the symmetric mixed strategy equilibrium. Thus we are unable to assign a reasonable common parameter to reflect the degree of error for this equilibrium.

Moreover it is easy to show from (26) that, if we fix $\alpha = 1$ and posit that the error occurs only when the signals disagree, we have $\beta(\lambda) \geq 1/2$ for any $\lambda \in [0,\infty)$. This is inconsistent with the data which indicatesβ around 32-35% (Table 2).

9 Appendix III: Treatments without Expert Information

We use two treatments without expert information as controls, and those are also a direct test of the Condorcet jury. As we saw on Table 5 the frequency of of our subjects voting according to their private signal was 84.7% in the seven-person committees and 91.4% in the fifteen-person committees. The main reason why the seven-person committees with expert information performed better than the seven-person committees without expert information, despite the fact that the outcome of the former approximated that of the inefficient obedient equilibrium, is that the subjects in the seven-person committees without expert information did not play according to the equilibrium and efficient strategy often enough. The difference in the frequency between the seven-person and fifteen-person committees without expert signal also is inconsistent with the notion of Quantal Response Equilibrium because according to QRE, the agents'

Table 7: Random effects probit: dependent variable = 1 if voted for private signal

	7-person comm. (2478 obs.)			15-person comm. (2655 obs.)		
Period	0.0003	0.0003	0.0002	0.0004	0.0004	0.0005
	(0.0022)	(0.0022)	(0.0022)	(0.0025)	(0.0025)	(0.0025)
Correct group decision in last period	0.1213	0.1129	0.2512**	0.0850	0.0874	0.2259
	(0.0793)	(0.0800)	(0.1260)	(0.1115)	(0.1118)	(0.1711)
Correct signal in last period		0.0615	0.2106		-0.0258	0.1664
		(0.0783)	(0.1310)		(0.0910)	(0.2035)
Correct signal in last period ×			-0.2346			-0.2400
Correct decision in last period			(0.1654)			(0.2276)
Constant	1.5223***	1.4914***	1.4235***	2.1564***	2.1697***	2.0672***
	(0.2273)	(0.2308)	(0.2368)	(0.2723)	(0.2764)	(0.2923)
Log likelihood	-800.8878	-800.5792	-799.5695	-584.6741	-584.6338	-584.0777

Note: Standard errors in parenthesis.

*** significant at 1% level; ** significant at 5% level; * significant at 10% level

non-equilibrium behaviour (mistakes) should be more pronounced when the loss from a mistake is small, which implies that subjects should vote according to the private information more often in the seven-person committees than in the fifteen-person committees.

The exact cause of the difference in the voting behaviour is difficult to determine, but Table 7 suggests that, at least in the seven-person committees, the subjects may have been "experimenting" with voting against their private signal especially after the committee decision in the previous period was incorrect. This type of (irrational) experimentation would result in a larger proportion of votes for the private signal in *larger* committees.

10 Appendix IV: Experimental Instructions[23]

Thank you for agreeing to participate in the experiment. The purpose of this session is to study how people make group decisions. The experiment will last approximately 55 minutes. Please switch off your mobile phones. From now until the end of the session, no communication of any nature with any other participant is allowed. During the experiment we require your complete, undistracted attention. So we ask that you follow these instructions carefully. If you have any questions at any point, please raise your hand.

The experiment will be conducted through computer terminals. You can earn money in this experiment. The amount of money you earn depends on your decisions, the decisions of other participants, and luck. All earnings will be paid to you immediately after the experiment. During the experiment, your payoff will be calculated in points.

[23]The instructions here are for the treatments with fifteen-person committees and expert information. The instructions for the other treatments are available on request.

After the experiment, your payoff will be converted into British Pounds (GBP) according to the following exchange rate: 850 points = £1, and rounded to the nearest pound. Please remain seated after the experiment. You will be called up one by one according to your desk number. You will then receive your earnings and will be asked to sign a receipt.

All participants belong to a single group of fifteen until the end of this experiment.

The experiment has two parts and consists of a total of 70 rounds. The first part of the experiment has10 rounds, and the second part has 60 rounds.

At the beginning of each round, the computer places a prize in one of two virtual boxes: a blue box and a yellow box. [SHOW PICTURE ON FRONT SCREEN] The location of the prize for each round is determined by the computer via the toss of a fair coin: at the beginning of each round it is equally likely that the prize is placed in either box. That is, the prize is placed in the blue box 50% of the time and the prize is placed in the yellow box 50% of the time. You will not directly see in which box the prize is hidden, but as we will describe later you will receive some information about it. [SHOW PICTURE ON FRONT SCREEN] The box that does not contain the prize remains empty.

The group's task is to choose a colour. In every round, each group member has two options, either to vote for BLUE or YELLOW. [SHOW PICTURE ON FRONT SCREEN] The colour that has received the majority of the votes becomes the group decision for the round. In every round, each member of the group earns:

1. 100 points if the group decision matches the colour of the box that contains the prize;

2. 5 points if the group decision does not match the colour of the box that contains the prize.

Note that your payoff for each round is determined exclusively by the group decision. If the group decision is correct, every group member earns 100 points. If the group decision is incorrect, every group member earns 5 points. The payoff is independent of how a particular group member voted.

To summarize, each round proceeds as follows: [SHOW PREVIOUS PICTURES IN TURN]

1. the computer places a prize in one of two boxes (blue box or yellow box with equal chance);

2. each group member receives some information about the location of the box;

3. each group member votes for BLUE or YELLOW;

4. group decision is the colour that has received most votes;

5. each group member receives earnings according to the group decision and the actual location of the prize.

Consider the following example. Suppose you and six other member voted for BLUE and the eight other members voted for YELLOW. This means that the group decision is YELLOW.

If the prize was indeed placed in the yellow box, then each group member, including you, earns 100 points. On the other hand, if the prize was placed in the blue box, each group member, including you, earns 5 points.

The experiment is divided into two parts. Both parts follow what we have described so far, but they are different in terms of i) the information each group member receives before voting, and ii) the number of rounds.

Part 1

The first part of the experiment will take place over 10 rounds. In each round, after the prize is placed in one of the two boxes but before group members vote, each participant receives a single piece of information about the location of the prize. We will call this type of information Private Information. Private Information will be generated independently and revealed to each participant separately, and it can be different for different group members. No other participants of the experiment will see your Private Information. [SHOW SCREEN FOR DECISION]

Private Information is not 100% reliable in predicting the box containing the prize. Reliability refers to how often Private Information gives the correct colour of the box.

Specifically, Private Information gives each of you the colour of the box with the prize 65% of the time, and the colour of the empty box 35% of the time.

The reliability of Private Information can be described as follows:

1. In each round, after the prize is placed in one of the boxes, the computer rolls a fair 20-sided dice for each group member. A real 20-sided dice is on your desk to help your understanding.

2.

a. If the result of the dice roll is 1 to 13 (1,2,4,5,6,7,8,9,10,11,12 or 13), then that member's Private Information is the colour of the box with the prize. Note that 13 out of 20 times means 65%.

b. If the result of the dice roll is 14 to 20 (14,15,16,17,18,19 or 20), then that member's Private Information is the colour of the empty box. Note that 7 out of 20 times means 35%.

Private Information is more likely to be correct than incorrect. Also, all group members receive equally reliable Private Information. However, since it is generated independently for each member, members in the same group do not necessarily get the same information. It is possible that your Private Information is BLUE while other members' Private Information is YELLOW.

Finally, at the end of each round, you will see the number of votes for BLUE, the number of votes for YELLOW, and whether the group decision matched the colour of the box with the prize.

Part 1 will start after a short quiz to check your understanding of the instructions. [PART 1 COMMENCES]

Part 2

The second part of the experiment will take place over 60 rounds. In each round, after the prize is placed in one of the two boxes but before group members vote, each group member receives two pieces of information, namely Private Information and Public Information, about the location of the prize. [SHOW SCREEN FOR DECISION] As before, in each round Private Information will be generated independently and revealed to each group member separately, and no other participants of the experiment will see your Private Information. It gives each of you the colour of the box with the prize 65% of the time, and the colour of the empty box 35% of the time.

The reliability of Private Information can be described as follows:

1. In each round, after the prize is placed in one of the boxes, the computer rolls a fair 20-sided dice for each group member.

2.

a. If the result of the dice roll is 1 to 13 (1,2,4,5,6,7,8,9,10,11,12 or 13), then that member's Private Information is the colour of the box with the prize. Note that 13 out of 20 times means 65%.

b. If the result of the dice roll is 14 to 20 (14,15,16,17,18,19 or 20), then Private Information is the colour of the empty box. Note that 7 out of 20 times means 35%.

In addition to but independently of Private Information, Public Information is revealed to all members of your group. In each round all group members get the same Public Information. It gives you the colour of the box with the prize 70% of the time, and the colour of the empty box 30% of the time.

The reliability of Public Information can be described as follows:

1. In each round, after the prize is placed in one of the boxes, the computer rolls a fair 20-sided dice (one dice roll for all members of your group), separately from the dice rolls for Private Information.

2.

a. If the result of the dice roll is 1 to 14 (1,2,4,5,6,7,8,9,10,11,12,13 or 14), then your group's Public Information is the colour of the box with the prize. Note that 14 out of 20 times means 70%.

b. If the result of the dice roll is 15 to 20 (15,16,17,18,19 or 20), then your group's Public Information is the colour of the empty box. Note that 6 out of 20 times means 30%.

Neither Public Information nor Private Information is 100% reliable in predicting the box with the prize, but both pieces of information are more likely to be correct than incorrect.

Note that those two pieces of information may not give you the same colour (it may be that one says BLUE and the other says YELLOW), in which case only one of them is correct. Public Information is more likely to be correct than each member's Private Information. However, it could be that your Private Information is correct and the Public Information is incorrect. Also, even if both pieces of information give you the same colour, it may not match the colour of the box that contains the prize, since neither is 100% reliable.

At the end of each round, you will see the number of votes for BLUE, the number of votes for YELLOW, and whether the group decision matches the colour of the box with the prize.

Part 2 will start after a short quiz to check your understanding of the instructions. [PART 2 COMMENCES]

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