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The impact of hypocrisy on opinion formation: A dynamic model

Michael T. Gastner[1,2]*, **Károly Takács**[2,3], **Máté Gulyás**[2,4], **Zsuzsanna Szvetelszky**[2], **Beáta Oborny**[4,5]

1 Division of Science, Yale-NUS College, Singapore, Singapore, **2** MTA TK "Lendület" Research Center for Educational and Network Studies (RECENS), Hungarian Academy of Sciences, Budapest, Hungary, **3** The Institute for Analytical Sociology (IAS), Linköping University, Norrköping, Sweden, **4** Department of Plant Taxonomy, Ecology and Theoretical Biology, Biological Institute, Loránd Eötvös University (ELTE), Budapest, Hungary, **5** GINOP Sustainable Ecosystems Group, Centre for Ecological Research, Hungarian Academy of Sciences, Tihany, Hungary

* michael.gastner@yale-nus.edu.sg

Abstract

Humans have a demonstrated tendency to copy or imitate the behavior and attitude of others and actively influence each other's opinions. In plenty of empirical contexts, publicly revealed opinions are not necessarily in line with internal opinions, causing complex social influence dynamics. We study to what extent hypocrisy is sustained during opinion formation and how hidden opinions change the convergence to consensus in a group. We build and analyze a modified version of the voter model with hypocrisy in a complete graph with a neutral competition between two alternatives. We compare the process from various initial conditions, varying the proportions between the two opinions in the external (revealed) and internal (hidden) layer. According to our results, hypocrisy always prolongs the time needed for reaching a consensus. In a complete graph, this time span increases linearly with group size. We find that the group-level opinion emerges in two steps: (1) a fast and directional process, during which the number of the two kinds of hypocrites equalizes; and (2) a slower, random drift of opinions. During stage (2), the ratio of opinions in the external layer is approximately equal to the ratio in the internal layer; that is, the hidden opinions do not differ significantly from the revealed ones at the group level. We furthermore find that the initial abundances of opinions, but not the initial prevalence of hypocrisy, predicts the mean consensus time and determines the opinions' probabilities of winning. These insights highlight the unimportance of hypocrisy in consensus formation under neutral conditions. Our results have important societal implications in relation to hidden voter preferences in polls and improve our understanding of opinion formation in a more realistic setting than that of conventional voter models.

1 Introduction

Public opinion is formed as a result of interrelated changes in individual opinions. Through a large number of social interactions, humans are greatly influenced by the opinions, attitudes,

and behavior of others. The dynamics resulting from these interactions have been studied in various models [1–9]. One of the most appealing and widely studied representations is the voter model due to its simplicity [10–14]. The paradigmatic voter model (which we will call the Basic Voter Model, BVM) represents the opinions of individuals as a binary variable in a single opinion dimension. At each update, an individual adopts the opinion of one of his acquaintances. In the BVM, every individual is assumed to express his inner conviction.

In practice, however, there might be a difference between an individual's publicly revealed and internal opinion. In the present paper, we focus on *hypocrisy* (i.e., individuals exhibit "self-censored" opinions in public [15]) and the abundance of *hypocrites* (i.e., individuals whose external and internal opinions differ). We study their frequency in the group and their role in the consensus-finding process.

Hypocrisy is abundant in all aspects of human social life. Voters withhold their true opinions in opinion polls, causing difficulties for the prediction of true outcomes [16–19]. Humans adjust their views and opinions to the circle in which they are present [20]. Social desirability is a general driver of expressing an opinion [21–23]. Even in the absence of direct influence or persuasion, individuals adjust their revealed opinion if they are exposed to the attitudes of others [24]. Actual behavior can fall very far from self-reports that are subject to social desirability bias, for instance in dietary intake [25], household labor [26,27], or physical activity [28]. Asch's classic experiments [29], in which he studied the influence of group pressure on individual opinions, show significant levels of conformity: participants of the experiments adopted the group's false opinion in a third of the trials, and more than half of the participants adopted a false group consensus at least once. Haun and Tomasello [30] demonstrated that, already at a young age, children try to say what they are expected to say without changing their own "real" judgment of the situation.

Many people attend church services without true faith, express popular opinions in discussions and meetings, follow a fashion trend they do not fancy, or adhere to regulations they disagree with. They show off with conspicuous consumption or by mowing their lawn while they have better things to do. People support morals they are not engaged with privately, have flexible virtues, and, following others, easily absolve themselves of moral responsibility [31–33].

Individuals might even openly support norms or legitimize a political system they privately do not sympathize with [34,35]. For example, Jiang and Yang [36] report quantitative evidence for "preference falsification" after a political purge in Shanghai in 2006. Laboratory experiments and computational models show that humans might punish norm violators in order to conform to group pressure against their own inner conviction [37,38]. The willingness to conform to social expectations might even lead to self-destructive behaviors such as binge drinking, shoplifting, and smoking among adolescents [39]. In extreme cases, this kind of hypocrisy can support a witch hunt, ostracism, or the public condemnation of scapegoats.

Hypocrisy is also a general feature of organizational behavior where reputation and promotions are at stake [40–42]. Within organizations, language use is often adjusted to the audience. For instance, the tone of political correctness depends on the expectations of receivers [43]. According to Noelle-Neumann [44], a significant proportion of people try to avoid isolation in the case of public questions. She posits that social relations and acceptance in their own environment are more important to people than revealing their own views in public.

All instances of hypocrisy create cognitive dissonance [45], which can be reduced mainly in two ways: internalization or externalization. In the case of internalization, the individual accepts the belief or opinion that he has expressed publicly [46]. Adjusting the internal opinion is an important last step in the process of socialization that is well described in the classic sociological and social psychological literature [47,48]. Opinions and individual attitudes are the products of contact with other members of the group that creates an internal and external

conflict "with its resolution based on the internalization of external norms" [49]. Internalization is distinct from compliance as it covers the private acceptance of the norm or attitude [46]. As a result, the individual can be said to be depersonalized and fully assimilated to the group [50,51].

In the case of externalization, the previously concealed opinion becomes publicly expressed. In practice, this requires courage or expressiveness. The "coming out" necessarily results in public discomfort, but often produces relief, a positive cognitive and emotional state. Acting and producing a poker face for the inhibition of inner opinions is certainly costly [52], and the individual is liberated from these costs by expressing his internal belief. It depends on the empirical context to which extent it is feasible to reduce cognitive dissonance by internalization or externalization. For instance, externalization is particularly problematic for political opinions in oppressive regimes, but strongly encouraged when diverse standpoints need to be revealed such as in critical academic debates.

The objective of this article is to analyze the role that hypocrisy, internalization and externalization play in opinion formation. As a more realistic alternative to the Basic Voter Model (BVM), we study the Concealed Voter Model (CVM), in which the publicly expressed (external) opinion can differ from the internal one [53]. Before we give a detailed definition of both models in **Section 2**, let us first state and motivate their underlying assumptions. The BVM and CVM share the following simplifications:

A. There are only two kinds of potential opinions (which we call "red" and "blue") on a particular issue, and these are mutually exclusive.

B. In the external layer, individuals interact in pairs.

C. The group is homogeneous in the sense that each rate is the same for all individuals and at all times.

D. Red and blue opinions have the same transition rates. That is, their competition is neutral.

Most versions of the voter model in the literature apply these simplifying assumptions (for reviews, see [12,14]). Extensions have relaxed some of the assumptions. For example, (A) was relaxed in the model by Vazquez and Redner [54], and (B) by Lambiotte and Redner [55]. Assumption (C) was relaxed by introducing zealots who never change their opinion [56,57] and (D) was relaxed in the biased voter model [58]. The CVM keeps (A)-(D) and adds an internal layer [53] (**Fig 1**). Some previous versions of the voter model have also considered a duality of opinions similar to our juxtaposition of external versus internal layer (e.g., [59,60]), but the internal opinions were static. A model that distinguishes between private and expressed opinions, but assumes continuous instead of binary opinions, was introduced by Ye et al. [61] and by Huang and Wen [62]. The CVM is the first discrete-state voter model in which the opinions in the internal layer can vary in response to the external layer within the individual, but not as a result of links to other internal opinions. In other multilayer voter models, nodes are connected in a multiplex network whose layers contain the same set of nodes with partially overlapping edges [63–67]. However, each layer in these multiplex models contains intra-layer edges so that none of the layers plays the role that the internal layer plays in the CVM: it contains private, hidden opinions that are unknown to other individuals.

Real-life examples for assumption (A) include those issues that are at stake in a social group and whose answer must be one of exactly two possibilities (e.g., yes/no or false/true). Many US elections, for instance, come down to a choice between only the Democrats or the Republicans. A recent example with exactly two alternatives on the ballot was the 2016 Brexit referendum, where voters could only choose between "remain" or "leave".
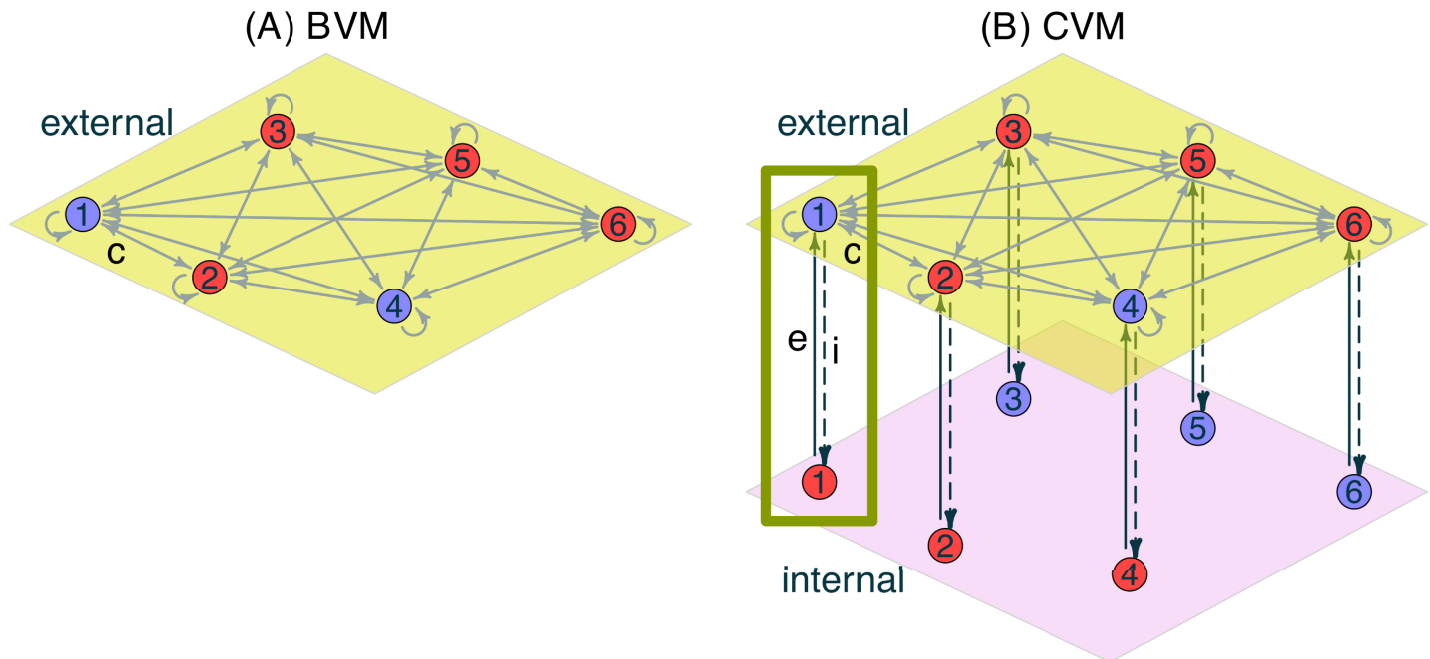
Fig 1. The Basic Voter Model (BVM) versus the Concealed Voter Model (CVM). *(A)* In the BVM, every individual is represented by a node in a single layer, which is "external" in the sense that all of its neighbors can see and copy his opinion. The tension that is caused by the disagreement between neighbors (for example between the blue individual 1 and the red individual 2) can be released by adopting the neighbor's opinion. Such copies happen with a rate *c*. *(B)* In the CVM, every individual is represented by two nodes: one in the external and another in the internal layer. For example, let us consider individual 1, outlined by the green rectangle. His external/internal opinion is marked by a blue/red circle. Because these opinions differ, we call individual 1 a "hypocrite". The tension between the external versus internal opinion can be released either by externalization or internalization (with the corresponding rates *e* and *i*). None of the individuals knows the internal opinion of any other individual. Hence, there are no edges within the internal layer.

Assumption (B) implies that external opinions can spread only from person to person so that the role of mass media is negligible. Mass media tend to portray the majority opinion as socially desirable and, hence, may increase the number of hypocrites in the population. Issues that are less influenced by mass media comply more with (B), for example newly trending issues (such as new slang expressions or underground music), shameful issues (e.g., norms of toilet use), or topics that are only of local or personal importance and interest (e.g., issues of taste, norms or habits in a small group or community).

Assumption (C) ensures an equal opportunity structure for the individuals in our model. It excludes the possibility that some of them can react to social influence, externalize, or internalize at a different rate from others. Assumption (D) guarantees that the dynamics does not give an intrinsic bias to one of the opinions. A typical asymmetry in real opinion formation may arise, for example, when one of the opinions provides more benefits in economic or social terms for the individuals than the other. We wish to exclude this kind of bias in order to study the process of spreading in a pure form. Thus, the BVM and the CVM can be used as neutral references to which more complex models or real-life systems can be compared.

Our previous results in the CVM have shown that, on average, the processes of internalization and externalization delay the consensus [53] because a minority opinion may still linger in the internal layer even when it has temporarily disappeared in public. In this paper, pursuing this path further, we ask fundamental questions about the role of hidden opinions and hypocrisy in the consensus formation process. We examine the proportion of hypocrites in the group over time and their effect on the dynamics of consensus formation. Our goal is to reveal

how hidden opinions influence the diversity of public opinions over time and how they shape the dynamics leading to eventual unanimity.

2 Methods

In the Basic Voter Model (BVM), the opinion of each individual is one node in a single, external network layer (**Fig 1A**). By contrast, the Concealed Voter Model (CVM) represents each individual by two nodes: one opinion in the external and another in the internal layer, which do not need to be identical (i.e., hypocrisy is possible). In the BVM and CVM, we model the external layer as a complete graph. We include a link from each node to itself. The models with and without the self-link are in fact merely reparameterized versions of each other (see S1 Appendix). We include the self-link because it simplifies the notation of the equation-based analysis in the S1 Appendix. While the external nodes are thus maximally connected with each other, every node in the internal layer is linked only to the external node representing the same individual (**Fig 1B**).

We call the alternative opinions "red" or "blue" and denote the opinions in the external versus internal layer by capital versus lower case letters (R: external red, r: internal red, B: external blue, b: internal blue). In the BVM, one letter is sufficient to characterize the state of every individual: R or B. We denote the fraction of agents in these states as ρ_R and $\rho_B = 1-\rho_R$. The group has reached a consensus when $\rho_R = 1$ or $\rho_B = 1$. In the CVM, we need two letters to describe the state: Rb (externally red hypocrite), Br (externally blue hypocrite), Rr (red frank) or Bb (blue frank). We denote the fraction of individuals in these states by ρ_{Rb}, ρ_{Br}, ρ_{Rr}, and ρ_{Bb} respectively. The state of the whole group can be described by the combination (ρ_{Rb}, ρ_{Br}, ρ_{Rr}). We do not need to explicitly include ρ_{Bb} because it is uniquely determined by $\rho_{Bb} = 1 -\rho_{Rb}-\rho_{Br}-\rho_{Rr}$. The abundances of internal and external opinions can be represented by the 2×2 matrix shown in **Table 1**. The proportion of hypocrites is $\rho_{Rb}+\rho_{Br}$. The group is in a consensus when $\rho_{Rr} = 1$ or $\rho_{Bb} = 1$. That is, we define a consensus as a state in which only one of the opinions exists; the alternative opinion has completely disappeared even from the internal layer.

For both models, the consensus time T_{cons} is defined as the duration between the initial state and the consensus. (Its synonyms are exit time, hitting time, or first-passage time; cf. [58,68]).

An agent-based Monte Carlo simulation of the BVM with N individuals proceeds according to the following algorithm.

1. *Initialization*: We initialize the opinions such that a given fraction ρ_R of the nodes are red. All other nodes are blue. We initialize time: $t \leftarrow 0$.

2. *Iteration*:

   i. We choose a "focal" individual f uniformly at random from all of the N individuals.

Table 1. *Contingency table showing the fraction of individuals with different combinations of external and internal opinions.*

		External opinion		
		R	B	sum
Internal opinion	r	ρ_{Rr}	ρ_{Br}	ρ_r
	b	ρ_{Rb}	ρ_{Bb}	ρ_b
	sum	ρ_R	ρ_B	1

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ii. We pick a neighbor n of the focal individual uniformly at random from all of its neighbors. (On a complete graph with self-links, all individuals are neighbors of each other so that n can be any individual in the group.)

iii. f adopts n's opinion. That is, if f and n have different opinions, we change f's opinion to that of n. Otherwise the system remains unchanged.

iv. We increment the time by a random number Δt drawn from an exponential distribution with mean $\frac{1}{cN}$, where c is a positive number: $t \leftarrow t + \Delta t$. We can interpret c as the rate with which individuals copy opinions of any of their neighbors.

v. If all nodes have the same color (i.e., the individuals have reached a consensus), we set $T_{\text{cons}}^{(\text{BVM})} \leftarrow t$ and terminate. Otherwise we go back to step (i).

Compared to the BVM, the CVM adds two options to step (ii): besides copying a neighbor's external opinion, individuals may also externalize or internalize (**Fig 1B**) to reduce cognitive dissonance as described in **Section 1**. We model copying, externalization and internalization as independent Poisson processes with rates c, e and i, respectively, according to the following agent-based algorithm.

1. *Initialization*: We initialize the opinions so that

   - a given fraction ρ_{Rb} of the individuals is externally red and internally blue,

   - a given fraction ρ_{Br} is externally blue and internally red,

   - a given fraction ρ_{Rr} is red in both layers,

   - the rest is blue in both layers.
     We also initialize time: $t \leftarrow 0$.

2. *Iteration*:

   i. We choose a "focal" individual f uniformly at random from all of the N individuals.

   ii. We generate a random number u that is uniformly distributed between 0 and $c+e+i$. We now distinguish between three cases.
   Case (A): *Copying*. If $u<c$, then f adopts the opinion of a random neighbor and we immediately go to step (iii).
   Case (B): *Externalization*. Otherwise, if $c \leq u < c+e$, then f externalizes. That is, if the current state of f is Rb, we change its state to Bb. If the current state is Br, we change f's state to Rr. For all other current states, the system does not change. We subsequently go immediately to step (iii).
   Case (C): *Internalization*. Otherwise f internalizes. That is, if the current state of f is Rb, we change its state to Rr. If the current state is Br, we change f's state to Bb. In all other cases, the system does not change.

   iii. We increment the time (i.e., $t \leftarrow t + \Delta t$) by a random number Δt drawn from an exponential distribution with mean $\frac{1}{(c+e+i)N}$. We can interpret $c+e+i$ as the rate with which individuals are active because they copy, externalize, or internalize.

   iv. If all nodes have the same color (i.e., all internal and external opinions are identical), we set $T_{\text{cons}}^{(\text{CVM})} \leftarrow t$ and terminate. Otherwise we go back to step (i).

We show snapshots of two illustrative sample runs of the CVM algorithm in **Fig 2**.
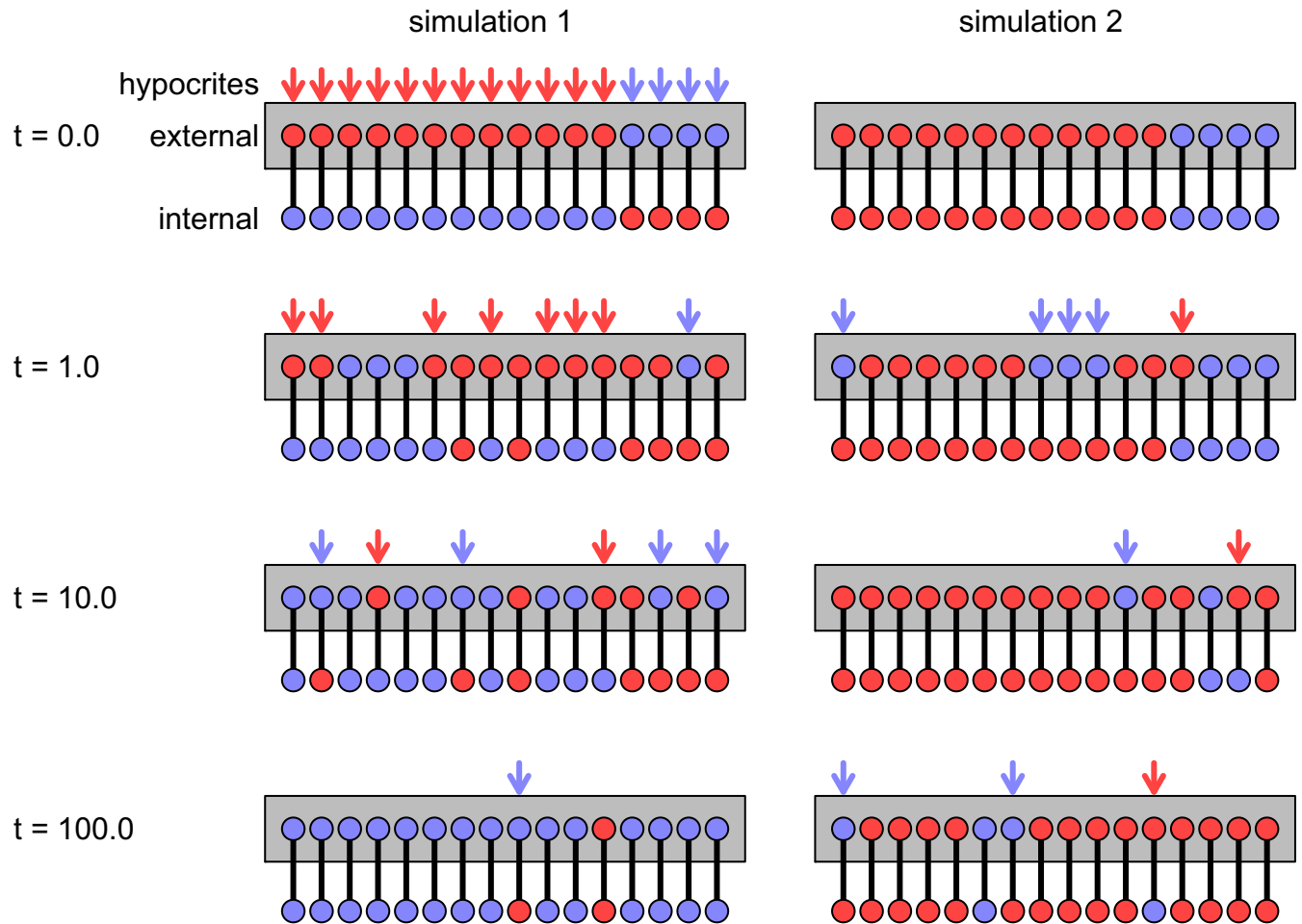
simulation 1   simulation 2

Fig 2. Two illustrative simulations in a relatively small group (*N* = 16 individuals). Each panel shows the state of the group at a given time from *t* = 0.0 to 100.0. (We write time with a decimal point because it is a continuous variable in our model.) The update rates are *c* = 1,*e* = 1/4, and *i* = 1/16. In each snapshot, the upper/lower nodes show the external/internal opinions (red or blue). In the external layer, the nodes are linked in a complete graph. We do not show the links, only indicate full connectedness by a gray box. (The reflexive self-link is also included. Therefore, every individual is linked with *N* = 16 individuals within the external layer.) The link between each individual's external and internal opinion is represented by a vertical line. Arrows mark those individuals who are hypocrites. The color of the arrow shows the external opinion. Initially, both groups contain 12 *red and* 4 blue opinions in the external layer. The difference is in the occurrence of hypocrisy: in the left/right column, every individual is initially hypocritical/frank. By *t* = 100.0, one of the opinions has reached a significant majority in each simulation (i.e., the group is close to a consensus).

The agent-based BVM and CVM algorithms that we have presented in this section make the relation between the models and individual opinion formation explicit. However, in practice, the corresponding Gillespie algorithms [69], based on the transition rate matrices given in [53], produce numeric results for both models more efficiently and are mathematically equivalent. We have, therefore, implemented our simulations with the Gillespie algorithms. The source code is available from GitHub [70].

3 Consensus time in the BVM and CVM

The BVM has been studied by numerous authors during its 45-year history (for reviews, see [12,14]), while the CVM is relatively new [53]. Here we review the main results concerning the consensus time in complete graphs. Both the BVM and the CVM lead to a consensus within a finite time, provided that the number of individuals *N* is finite (cf. [71] concerning the BVM

and [53] about the CVM). The only exception occurs when $i = 0$ in the CVM and both r and b are present in the internal layer. In that special case, r and b persist for an infinitely long time.

In the BVM, the mean consensus time in the complete graph is [58]

$$T_{\text{cons}}^{(\text{BVM})}(\rho_R) = -\frac{N}{c}[\rho_R \ln \rho_R + (1 - \rho_R)\ln(1 - \rho_R)], \qquad (1)$$

where N is the number of individuals, c is the copying rate, and ρ_R is the proportion of the red opinion in the external (i.e., only) layer at time $t = 0$. Note that $T_{\text{cons}}^{(\text{BVM})}$ is symmetric under the exchange of the red and blue opinions because $\rho_B = 1 - \rho_R$. For obtaining the mean consensus time in the CVM, it is worth introducing a new variable,

$$m(\rho_R, \rho_r) = \frac{i\rho_R + e\rho_r}{e + i}, \qquad (2)$$

where $\rho_R = \rho_{Rb} + \rho_{Rr}$ is the fraction of *externally* red individuals and $\rho_r = \rho_{Br} + \rho_{Rr}$ is the fraction of *internally* red individuals (**Table 1**). We can interpret m as the overall "strength" of the red opinion because it characterizes the actual weight of the red opinion in the group, as e and i express the flow of information between the two layers. The expected value of m remains constant throughout the process of consensus formation; that is, $m(\rho_R, \rho_r)$ is a martingale [53]. As a consequence, $m(\rho_R, \rho_r)$ is equal to the probability that the consensus in a group with initial conditions (ρ_R, ρ_r) is red. (We will show numerical evidence for this equality in **Section 4.3**.)

The mean consensus time $T_{\text{cons}}^{(\text{CVM})}$ in the CVM can be directly obtained from that in the BVM,

$$T_{\text{cons}}^{(\text{CVM})}(m) = \tau(c, e, i) \cdot T_{\text{cons}}^{(\text{BVM})}(m), \qquad (3)$$

where

$$\tau(c, e, i) = \frac{(c + e + i)(e + i)^2}{i[(e + i)^2 + ci]}. \qquad (4)$$

On one hand, because $\tau(c, e, i) > 1$, the mean consensus time is always longer in the CVM than in the BVM, given the same number of individuals N. Thus, the existence of hypocrisy in a group increases the consensus time. On the other hand, the probability m of a red consensus and the mean consensus time $T_{\text{cons}}^{(\text{CVM})}$ are fully determined by c, e, i, n, ρ_R, and ρ_r (see **Eqs 2–4**), and thus do not depend on the amount of hypocrites ρ_{Rb} or ρ_{Br}. To resolve this paradox, it is necessary to better understand the transient behavior of the CVM, particularly the role of hypocrites in the consensus-finding process. This observation motivated the present study.

4 Results

4.1 Consensus formation in the CVM

We study the changes in the state $(\rho_{Rb}, \rho_{Br}, \rho_{Rr})$ over time. **Table 2** and **Fig 3** present results from simulations for four different initial conditions. All these simulations were performed with the same parameters $N = 400$, $c = 1$, $e = 1/4$, and $i = 1/16$. We have also carried out simulations for various other parameter combinations and report representative results in the S2 Appendix. In **Table 2**, we denote by F the fraction of simulations in which the consensus is red. (In the table, we also list the equilibration time T_{equal} that we define and discuss in **Section 4.2**.) **Table 2** underlines the excellent agreement between theoretical prediction and numeric simulations. We also observe agreement for other parameters. We support this claim by showing the results for another parameter combination in the S2 Appendix.

Table 2. The four cases of CVM simulations that are displayed in Figs 3 and 4.

Symbol & Color		■	▲	◆	▼
Initial value	ρ_{Rb}	0.00	0.25	0.50	0.75
	ρ_{Br}	1.00	0.75	0.25	0.00
	ρ_{Rr}	0.00	0.00	0.25	0.00
F	Observed	0.81±0.02	0.65±0.03	0.57±0.03	0.17±0.02
	Predicted (*m*, see Eq 2)	0.80	0.65	0.55	0.15
$T_{\text{cons}}^{(\text{CVM})}$	Observed	2630±160	3270±160	3470±150	2090±140
	Predicted (Eq 3)	2563.0	3316.2	3524.6	2165.1
T_{equal}	Observed	3.23±0.05	3.23±0.11	3.14±0.23	3.15±0.07
	Predicted (Eq 7)	3.2			

The top row shows the symbols and colors used in the figures. The next three rows show the initial conditions. The remaining rows compare measurements from simulations (N = 400, c = 1, e = 1/4, i = 1/16) with theoretical values. Each measurement is the sample mean of 1000 simulations. Uncertainties are given as 95% confidence intervals. It is noteworthy that the time until consensus $T_{\text{cons}}^{(\text{CVM})}$ is much longer than the equalization time T_{equal}. (See **Section 4.2** for the definition of T_{equal}.)

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We show in **Fig 3A and 3B** (and, for another parameter combination, in the S2 Appendix) that the process of consensus formation in all realizations takes place in two stages. The first stage is relatively short and is dominated by a directional change in the group's composition: the trajectories go toward an attractor, which is an arch-shaped curve (plotted as a black curve in **Fig 3**). The S1 Appendix shows that the curve is given by

$$\rho_{Rb} = \rho_{Br} = \frac{\sqrt{(e+i)^2 + 4c(c+e+i)\rho_{Rr}} - (e+i)}{2c} - \rho_{Rr}. \tag{5}$$

The second stage of consensus formation is characterized by a random walk along this curve. The deviations of the trajectories from the theoretical curve are caused by the finite size of the simulated system (N = 400). The walk ends by reaching one of the two consensus states (i.e., $\rho_{Rb} = \rho_{Br} = 0$ and either $\rho_{Rr} = 0$ or $\rho_{Rr} = 1$). The direction of each step in the walk is randomly selected. However, unlike in conventional unbiased random walks, the frequency of steps is decreasing as the consensus is approached because most copying events are between like-minded individuals. Moreover, near the consensus, there are only few hypocrites left so that externalization and internalization are also unlikely to change the state.

It is interesting to observe the wide range of the walk in the second CVM stage. For example, the trajectory indicated by purple diamonds in **Fig 3C** ends in a consensus in which the blue opinion wins (i.e., $\rho_{Rb} = \rho_{Br} = \rho_{Rr} = 0$); nevertheless, the trajectory goes through some points in which $\rho_R > 0.5$, (i.e., the red opinion is temporarily the majority in the external layer). The probability of a reversal from an external red majority $\rho_R(t) > 0.5$ at time t to a blue consensus is equal to $1 - m[\rho_R(t), \rho_r(t)]$, where m is given by **Eq 2**. We note that this probability does not depend on the system size because m is independent of N.

4.2 Equalization of the number of hypocrites

There are two kinds of hypocrites: *Rb* (i.e., externally red) and *Br* (externally blue). We denote the difference in the abundances by $D = \rho_{Rb} - \rho_{Br}$. In **Fig 3A**, we see that the abundances of the two kinds of hypocrites tend toward equality in the first stage of consensus formation (i.e., $\overline{D} \to 0$, where the overline denotes the mean, averaged over different simulations). A projection of the data onto the (ρ_{Rb}, ρ_{Br}) plane (**Fig 3B**) shows this tendency even more clearly. The black line (i.e., the projection of the attractor) is exactly on the diagonal.
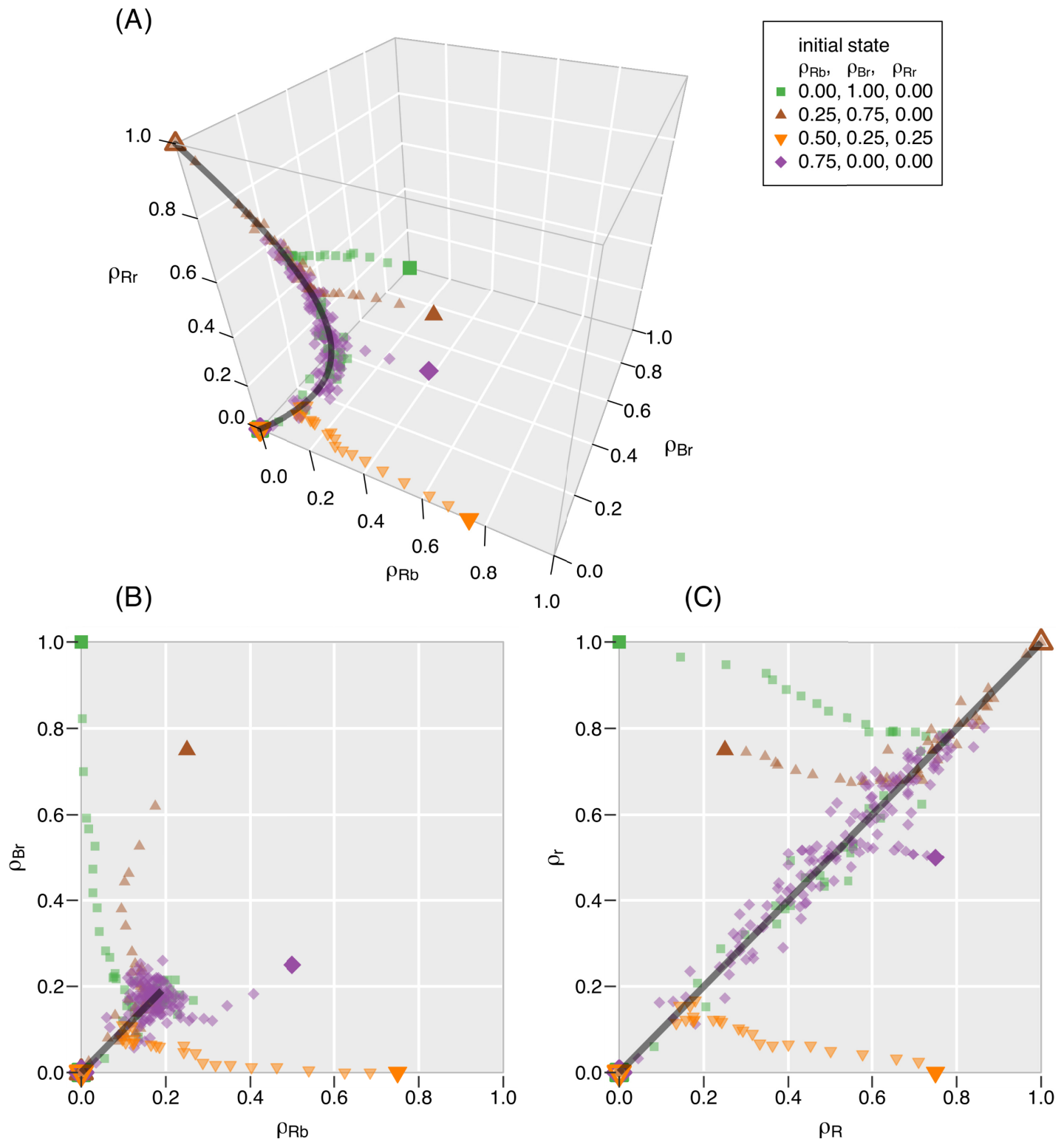
Fig 3. Changes in the composition of the group over time in four realizations of the CVM. Each point belongs to one "snapshot" between the initial state (large, filled symbols) and the consensus (large, open symbols). The parameters for all simulations are $N = 400$, $c = 1$, $e = 1/4$, $i = 1/16$. We show only a single simulation for each initial condition, but we note that repeated simulations from the same initial state can end in either of the absorbing states unless the initial state is already a consensus. The time intervals between the plotted points change along the trajectories: during the transient, we plot every 100th time step until the 2000th time step. Afterwards we plot only every 10000th time step because the spatial density of data points is higher along the attractor. **(A)** Abundances of the two kinds of hypocrites (ρ_{Rb} and ρ_{Br}) and

the proportion of frank red individuals (ρ_{Rr}). These variables completely describe the state of the system. The theoretical attractor (**Eq 5**) is shown as a black curve. **(B)** Equalization of the two kinds of hypocrites in the same realizations. In a consensus, there are no hypocrites (i.e., $\rho_{Rb} = \rho_{Br} = 0$). Therefore, the open symbols at the consensus overlap. The attractor appears as a straight line because it is a two-dimensional projection of the curve embedded in three dimensions. The line is exactly on the diagonal. **(C)** Equalization of the abundance of the red opinion in the external ($\rho_R = \rho_{Rb} + \rho_{Rr}$) and internal layer ($\rho_r = \rho_{Br} + \rho_{Rr}$). The attractor (black line) is exactly on the diagonal.

To examine this phenomenon in more detail, we plot the absolute value of $\overline{D}(t)$ from $t = 0.0$ to 10.0 (**Fig 4**). The data points were obtained from 1000 independent repetitions. As we derive in the S1 Appendix, we expect

$$\overline{D}(t) = D_0 \cdot \exp[-(e+i)t]. \tag{6}$$

(A rigorous proof is given in [53].) The straight lines in **Fig 4** indicate the theoretical predictions, which are an excellent fit to the numeric data.

In **Fig 3**, we illustrate that the equalization process is relatively fast compared to the subsequent random walk on the attractor. Let us define the equalization time T_{equal} as the time t satisfying $\overline{D}(t) = D_0 \cdot \exp(-1)$,

$$T_{\text{equal}} = \frac{1}{e+i}. \tag{7}$$

In the logarithmic plot of **Fig 4**, T_{equal} is proportional to the inverse of the slope. The plotted examples and the last two rows of **Table 2** confirm that T_{equal} is independent of the initial conditions. **Table 2** also shows that T_{equal} is much shorter than the mean consensus time $T_{\text{cons}}^{(\text{CVM})}$. For the chosen rates ($c = 1$, $e = 1/4$, $i = 1/16$), $T_{\text{cons}}^{(\text{CVM})}$ is longer than T_{equal} by around three orders of magnitude. The precise ratio of $T_{\text{cons}}^{(\text{CVM})}$ to T_{equal} depends on the initial conditions and the parameters c, e, i and N. In particular, $T_{\text{cons}}^{(\text{CVM})}$ increases linearly with N (see **Eqs 1** and **3**), but T_{equal} is independent of N. So, even for only moderately large group sizes, the CVM spends most of the time during consensus formation in the second, random walk stage. Simulations with a different parameter combination (S2 Appendix) provide further evidence for the generality of this result.

The number of hypocrites is not the only observable that equalizes in the first stage. We show in **Fig 3C** that the abundance of the red opinion becomes equal in the public (external) and in the concealed (internal) layer (i.e., $\overline{\rho_R - \rho_r} \to 0$). The time of equalization is exactly the same as in the case of hypocrites above. The reason is that, because of $\rho_{Rb} = \rho_R - \rho_{Rr}$ and $\rho_{Br} = \rho_r - \rho_{Rr}$, we obtain

$$D = \rho_{Rb} - \rho_{Br} = \rho_R - \rho_r. \tag{8}$$

Consequently, T_{equal} applies as much to the equalization of the abundances between the two layers as it applies to the equalization of hypocrite types.

It is important to note that the ratio of red to blue is the same in both layers during the second stage, which is the predominantly longer stage during the process of consensus formation. This observation suggests that estimating the abundance of an opinion in the public layer gives a good prediction for the abundance in the concealed layer. (We consider the implications of this result in **Section 5.1**.) The statement refers, of course, to the *averages* in the population. The *individuals* who bear these opinions can be different at different times. Furthermore, **Eq 6** neither predicts ρ_{Rb} nor ρ_{Br}, only the mean difference $\overline{D} = \overline{\rho_{Rb} - \rho_{Br}}$. At some parameter combinations, we temporarily find a considerable amount of hypocrites before reaching a consensus, while for other combinations most of the individuals are frank.
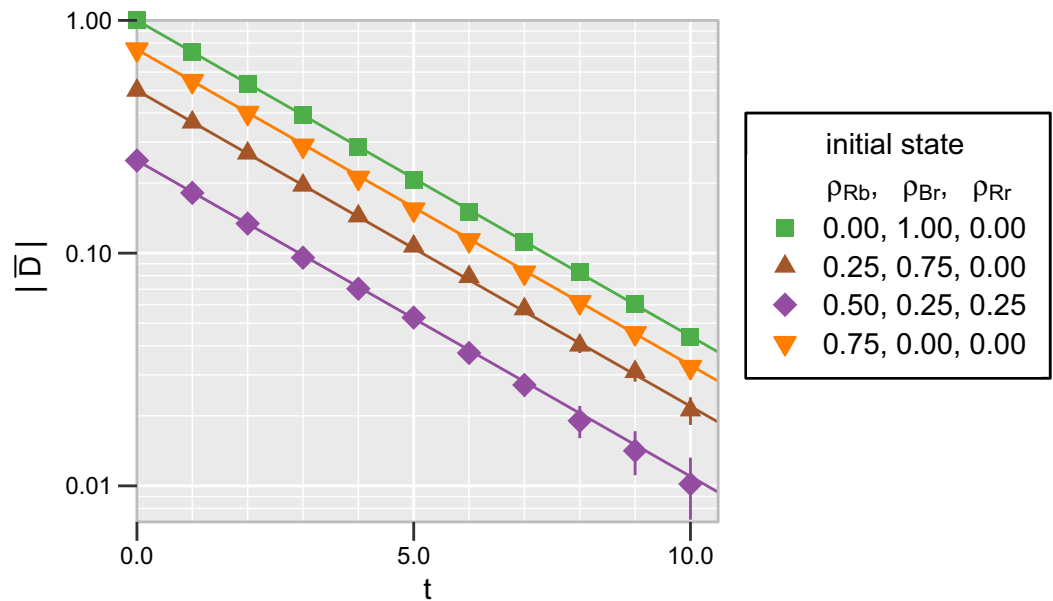
Fig 4. Equalization of the two kinds of hypocrites over time. The parameter values are the same as in **Fig 3**. The initial conditions are also the same for the corresponding shapes and colors. The vertical axis shows the absolute value of the mean difference $\overline{D} = \overline{\rho_{Rb} - \rho_{Br}}$ on a logarithmic scale. The mean was obtained from 1000 independent realizations. The error bars are shown only where they are larger than the symbol sizes. The solid lines are theoretical predictions under the assumption that $\overline{D}$ decays exponentially with rate e+i (**Eq 6**).

4.3 The (un)importance of hypocrisy

As we pointed out earlier, the opinion dynamics on a complete graph must end in either a red or blue consensus (provided that the number of individuals N is finite). How do the initial conditions and the rates c, e and i influence which opinion is going to win (i.e., becomes the consensus opinion)?

Fig 5 shows theoretical predictions together with simulation results. We show in **Fig 5A** that the frequency F of red winning is equal to the initial value of m, defined in **Eq 2**. Since the formula for m does not contain c, the probability of winning does not depend on the communication at the external layer, but only on the interaction *between* the external and internal layer (expressed by e and i). Another noteworthy result is that the abundances of the hypocrites ρ_{Rb} and ρ_{Br} do not appear in **Eq 2** either. They are implicitly present in the equation because $\rho_R = \rho_{Rb} + \rho_{Rr}$ and $\rho_r = \rho_{Br} + \rho_{Rr}$. However, to predict the eventual winner, it is sufficient to know only two variables, namely ρ_R and ρ_r. In fact, after the attractor (given by **Eq 5**; black curve in **Fig 3**) has been reached, we do not even need to know ρ_r any longer. By that time, the abundances in both layers are, on average, equal (see **Fig 3C**). So the probability of a red victory is directly given by the abundance ρ_R of red in the *external* layer, which is easier to observe in real life than the *internal* abundance ρ_r.

Unlike F, the mean consensus time $T_{\text{cons}}^{(\text{CVM})}$ does depend on c and N. This statement follows from the combination of **Eqs 1**, **3** and **4**,

$$T_{\text{cons}}^{(\text{CVM})} = -\frac{N(c + e + i)(e + i)^2}{ci[(e + i)^2 + ci]}[m \ln(m) + (1 - m)\ln(1 - m)]. \qquad (9)$$

We confirm this result with **Fig 5B**: data points for different N and c fall on different curves. Still, neither ρ_{Rb} nor ρ_{Br} appear explicitly in **Eq 9**. Consequently, m is all we need to know about the initial condition in order to predict $T_{\text{cons}}^{(\text{CVM})}$. After we have reached the attractor, m is
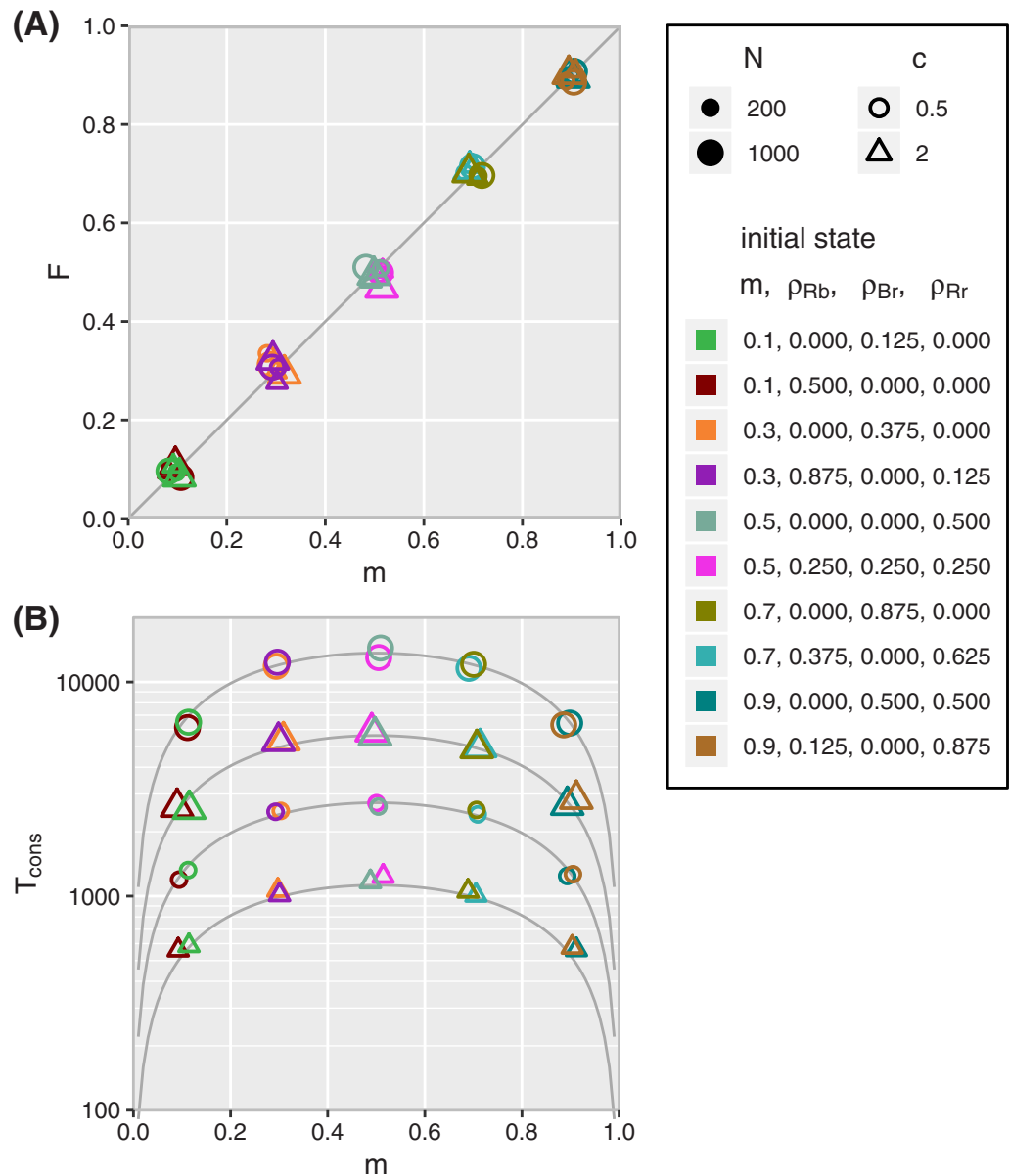
Fig 5. The consensus distribution and consensus time in the CVM. Numeric results confirm that these properties of the CVM depend only on m (defined in Eq 2), the initial strength of the red opinion. (In the plot, we have deliberately added jitter in the horizontal direction to make individual data points visible. Otherwise the overlap would obscure that there are multiple points on top of each other.) Each symbol shows the mean of 1000 simulations. All simulations use e = 1/4 and i = 1/16. N, c, and the initial conditions vary. (N is symbolized by the size, c by the shape, and the initial condition by the color; see legend.) **(A)** Proportion of simulations in which the red opinion wins (F) as a function of the initial strength of red [m(t = 0)]. The diagonal line indicates F = m. The overlapping symbols exemplify that simulations with different initial conditions produce the same F if the initial m is the same, despite different abundances of hypocrites. **(B)** The mean consensus time $T_{cons}^{(CVM)}$ as a function of m. The gray curves are theoretical predictions from **Eq 9**, which is derived under the assumption that N is large [53]. The simulations confirm that **Eq 9** is a good approximation even for moderately large N. For different N and c, the values of $T_{cons}^{(CVM)}$ fall on different curves. However, for given N and c, $T_{cons}^{(CVM)}$ depends only on m, but not on any further details of the initial conditions.

equal to ρ_R so that we can, at that stage, make a prediction for the mean consensus time simply by observing the abundance of the red opinion in the external layer.

5 Discussion

5.1 The symmetry of hypocrisy

We studied the role of hypocrisy in a relatively simple model, the CVM in a complete graph. The CVM extends the original voter model (BVM) by incorporating an internal opinion that can be different from the external one (i.e., hypocrisy can occur).

In the CVM, each individual is exposed to two kinds of tension during the process of opinion formation,

a. tension caused by the disagreement with another individual and

b. cognitive dissonance [45] caused by a difference between the external and internal opinion of the individual.

Adopting the external opinion of a disagreeing neighbor releases tension (a). Externalization or internalization releases (b). In some cases, both types of tension can be simultaneously annihilated. In other cases, the reduction of one type of tension can directly lead to new tension of another type.

We showed that the consensus process in the CVM consists of two stages,

1. approaching the attractor (given by **Eq 5**) from the initial state and

2. a random walk on the attractor.

A characteristic feature of the attractor is $\rho_{Rb} = \rho_{Br}$. That is, the hypocrites of both types (externally red and externally blue) are expected to be equally abundant, regardless of whether R or B is in a majority. For realistic parameters, stage 1 is much shorter than stage 2 so that $\rho_{Rb} \approx \rho_{Br}$ for almost the entire duration of opinion formation. In particular, in the CVM even a great imbalance of opinions in the public layer (in our notation, a great difference between ρ_R and $\rho_B = 1 - \rho_R$) is accompanied by a balance of opinions among hypocrites (i.e., a small difference between ρ_{Rb} and ρ_{Br}).

A second equality follows directly from the equalization of the hypocrites and **Eq 8**: $\overline{\rho_R - \rho_r} \to 0$. This means that the representation of the red opinion becomes the same in the external and the internal layer. This result might have some noteworthy consequences for opinion polls. Traditional survey methods sample the external layer only. In general, it is difficult to reach the internal layer (i.e., to get information about the concealed opinions) due to privacy or sensitivity concerns. In many cases, however, it would be crucial to know opinions hidden in the internal layer, especially when the action of the person is more strongly influenced by the internal than the external opinion. Examples include decisions whether to buy or consume a particular product or read an online source of information. Another example are elections, where the internal opinion is expressed by an action (e.g., voting for a party) without revealing the vote in public. Exit polls and surveys that mimic a secret ballot attempt to directly measure the internal layer.

The main consequence of our results is that a poll that asks only about the *external* opinions may still make a good estimate about the *internal* opinions as well, at least at the group level, assuming that there is no external desirability bias that would differentiate between the public expressions of the two opinions. Political polls are examples in which respondents can show a "public" face so that the internal opinion of many participants may remain hidden. This is even more likely in focus group studies or in a public discourse. If $\rho_R = \rho_r$ holds, then this tendency does not make the poll invalid: the result of the poll may in fact be fairly accurate in spite of the occurrence of hypocritical answers. A remarkable result in the CVM is that neither the majority nor the minority opinions are externally overrepresented because of hypocrisy. In

a neutral context without a media bias and an exogenous desirability bias, there is no expected difference between bandwagon and underdog hypocrisy.

5.2 How to shorten or prolong the consensus time

A long consensus time may be disadvantageous, for example, when a coordinated action is needed in a group. For instance, this is the case in jury decision making, which has been studied extensively [72–76]. Conversely, delaying a consensus may be desirable in those situations, in which the diversity of opinions is valuable. We have pointed out in **Section 4.2** that $T_{\text{cons}}^{(\text{CVM})}$ increases linearly with N so that one strategy to delay a consensus simply is to expand the group size. The linear scaling of the consensus time with N, however, is not specific to the CVM. We find the same scaling relation in the BVM too (see **Eq 1**). Besides changing the group size, which properties of the concealed layer influence the consensus time?

We know from **Eq 4** that the delay τ depends only on the copying rate c, the externalization rate e, and the internalization rate i. If these rates are positive, we have $\tau > 1$ so that the CVM needs more time to reach consensus than the BVM with the same value of c [53]. For example, for the parameter combination used in **Table 2** ($c = 1$, $e = 1/4$, $i = 1/16$), we obtain $\tau \approx 12.8$; that is, the CVM needs on average around one order of magnitude longer to reach a consensus. We are not aware of any empirical study that suggests specific values for e or i. To investigate the effect of varying e and i, we carry out simulations in the S2 Appendix where we swap their value compared to **Table 2** (i.e., $c = 1$, $e = 1/16$, $i = 1/4$). In that case, the consensus time is shorter, as predicted by **Eq 3**.

It is instructive to consider the limiting cases of the CVM if the rates e or i are extremely fast or slow. On one hand, in the limit $i \to \infty$ we would have simply retrieved the BVM. The prediction of **Eq 4** is, accordingly, $\tau \to 1$ in this limit. On the other hand, increasing e and decreasing i can enhance the consensus time to enormous values. Thus, to maintain a longer coexistence of alternative opinions, one could aim to increase e, for example by encouraging self-expression [77–79], whereas decreasing i is more difficult to accomplish in real life because the institutions of socialization (school, work, the state, and the media) are well established. In the limit $i \to 0$, $T_{\text{cons}}^{(\text{CVM})}$ goes to infinity. The reason for this divergence is that, in this case, the internal layer does not change at all so that any disagreement in the internal layer remains frozen in time.

The zealot voter model, introduced by Mobilia et al. [57], applies the limit $i \to 0$ together with $e \to \infty$ for a certain fraction of the group. These "zealots" never change their internal opinion and always express this opinion openly. Some other models in the literature can also be "translated" into two-layer voter models with fixed internal states (i.e., $i \to 0$). For example, there are models with "inflexible minorities" [80], "stubborn agents" [81], or "partisans" [59,60], in which the individuals have a fixed and innate preference for one of the (external) states. To the best of our knowledge, the CVM is the first model in which the internal layer can change so that the interaction between the two layers is bidirectional.

The winning opinion is not necessarily a majority opinion; for instance, as Nemeth and Wachtler [82] expressed, consistent minority views can affect other members of a jury whilst reaching their verdict in fictional courts. Minority opinions can also have an impact on public discourse in social questions such as feminism, the death penalty, or homosexuality [79,83,84].

The interplay between the layers slows down the CVM compared to the BVM, but, interestingly, the number of hypocrites is not directly responsible for the deceleration. As we pointed out above, the hypocrite abundances ρ_{Rb} and ρ_{Br} do not appear explicitly in the formulas for m and $T_{\text{cons}}^{(\text{CVM})}$ (see **Eqs 2** and **9**). In other words, both m and $T_{\text{cons}}^{(\text{CVM})}$ are determined by the marginal frequencies in **Table 1** (i.e., ρ_R and ρ_r) alone, which do not uniquely determine the joint

frequencies ρ_{Rr}, ρ_{Br}, ρ_{Rb}, and ρ_{Bb}. For example, a group with $\rho_R = 1/2$ and $\rho_r = 1/2$ may consist purely of hypocrites ($\rho_{Rb} = \rho_{Br} = 1/2$, $\rho_{Rr} = \rho_{Bb} = 0$) or purely of frank individuals ($\rho_{Rr} = \rho_{Bb} = 1/2$, $\rho_{Rb} = \rho_{Br} = 0$). The consensus time is the same in both cases.

In this sense, the CVM is slower than the BVM because of the mere existence of the concealed layer and, thus, because of the *opportunity* for hypocrisy, but not because of the *amount* of hypocrisy. The concealed layer serves as a pool of opinions. Hypocrisy necessarily emerges in such a system as a path from one opinion to another, but the amount of hypocrisy does not drive the consensus process.

6 Summary and outlook

This study presented and analyzed the Concealed Voter Model (CVM) as a relatively simple model of opinion dynamics with the possibility of hypocrisy (i.e., internal and publicly expressed individual opinions might differ). The study demonstrated that the process of consensus formation in the model takes place in two stages. The first stage is relatively short and is characterized by an equilibration in the number of hypocrites of both types ($\rho_{Rb} \approx \rho_{Br}$) or, equivalently, an equilibration in the opinions in both layers ($\rho_R \approx \rho_r$). The second stage is a random walk along an attractor to which the opinion distributions quickly converge. We investigated the time $T_{\text{cons}}^{(\text{CVM})}$ needed to reach a consensus and compared $T_{\text{cons}}^{(\text{CVM})}$ to the consensus time $T_{\text{cons}}^{(\text{BVM})}$ in the Basic Voter Model (BVM), in which hypocrisy is non-existent.

An important result is that hypocrisy always prolongs the mean time needed to reach unanimity of opinions. This result calls for policy measures that could eliminate or decrease the second stage of the dynamics in jury and committee decision making where consensus and fast decisions are highly desired, for instance by requiring a critical (high) threshold instead of unanimity [72,73].

As a second important result, the study showed that the number of both kinds of hypocrites equalize. This is good news for opinion pollsters who suffer from bias induced by hidden opinions. The model demonstrates that, in a neutral scenario, the numbers of both kinds of hypocrites balance each other out–so any empirical observation of bias is due to external factors or heterogeneous externalization and internalization rates that correlate with party preference.

As a third important result, the study demonstrated that in the CVM, just like in the BVM, the consensus time increases linearly with population size. This result is in line with observations that coordination in a larger group is more difficult, but not disproportionately more difficult than in a smaller group [72,74].

The simple CVM can be extended in multiple directions. So far, we have assumed that the links between individuals constitute a complete graph. It would be interesting to consider whether permitting different graph structures would change the results qualitatively. Previous work highlighted that the network structure is important for opinion dynamics in general [85]. In the BVM, networks with broad degree distributions shorten the time till consensus [58]. In a model similar to the BVM, Axelrod [86] has shown that minority opinions can survive and consensus may never be reached if network routes of influence are dissolved so that opinions are cut out completely from interactions with opposing opinions. Minority opinions are also likely to survive in models where network ties of influence are updated according to opinion homophily so that there is a co-evolution of networks and opinions [87–90].

Another way to increase realism is to consider nonbinary opinions. The previous literature has highlighted substantial differences between opinions measured on binary, continuous or nominal scales [91]. From an empirical perspective, it would also be desirable to study non-symmetric competition between the opinions. Asymmetry could be introduced, for instance, by a "media" effect that causes bias in one direction (e.g., in social influence or externalization)

[92–94] or by heterogeneous internalization rates that correlate with voter preferences. Beyond a constant media bias in one direction, one could study exogenous stimuli that alter the direction of the bias. Such an extension could potentially explain the occurrence of cyclical patterns that are not emergent from the current model, but are observable, for example, in fashion trends and public sentiments [95,96].

Despite the limitations, we believe that studies that permit concealed opinions have a lot of potential in understanding opinion dynamics because they incorporate an important feature of real-life opinions: not everything is expressed openly.

Supporting information

S1 Appendix. Derivation of Eqs 5 and 6.
(PDF)

S2 Appendix. Numerical simulations and theoretical predictions for a different set of parameter values: $c = 1$, $e = \frac{1}{16}$, $i = \frac{1}{4}$.
(PDF)

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Author Contributions

Conceptualization: Michael T. Gastner, Károly Takács, Máté Gulyás, Zsuzsanna Szvetelszky, Beáta Oborny.

Data curation: Máté Gulyás.

Formal analysis: Michael T. Gastner, Máté Gulyás.

Investigation: Michael T. Gastner, Beáta Oborny.

Methodology: Michael T. Gastner, Károly Takács, Máté Gulyás, Zsuzsanna Szvetelszky, Beáta Oborny.

Software: Michael T. Gastner, Máté Gulyás.

Visualization: Michael T. Gastner.

Writing – original draft: Michael T. Gastner, Károly Takács, Máté Gulyás, Zsuzsanna Szvetelszky, Beáta Oborny.

References

1. Latané B. The psychology of social impact. Am Psychol. 1981; 36: 343–356. https://doi.org/10.1037/0003-066X.36.4.343

2. Friedkin NE. Structural cohesion and equivalence explanations of social homogeneity. Sociol Methods Res. 1984; 12: 235–261. https://doi.org/10.1177/0049124184012003001

3. Friedkin NE. Choice shift and group polarization. Am Sociol Rev. 1999; 64: 856–875. https://doi.org/10.2307/2657407

4. Friedkin NE. Social influence network theory: toward a science of strategic modification of interpersonal influence systems. In: Breiger R, Carley K, Pattison P, editors. Dynamic social network modeling and analysis: workshop summary and papers. Washington, D.C.: The National Academies Press; 2003. pp. 89–100.

5. Friedkin NE. Social cohesion. Annu Rev Sociol. 2004; 30: 409–425. https://doi.org/10.1146/annurev. soc.30.012703.110625

6. Friedkin NE, Johnsen EC. Social influence networks and opinion change. Adv Group Process. 1999; 16: 1–29.

7. Axelrod R. An evolutionary approach to norms. Am Polit Sci Rev. 1986; 80: 1095–1111. https://doi.org/ 10.2307/1960858

8. Flache A, Macy MW. Local convergence and global diversity: from interpersonal to social influence. J Confl Resolut. 2011; 55: 970–995. https://doi.org/10.1177/0022002711414371

9. Friedkin NE, Bullo F. How truth wins in opinion dynamics along issue sequences. Proc Natl Acad Sci. 2017; 114: 11380–11385. https://doi.org/10.1073/pnas.1710603114 PMID: 29073060

10. Clifford P, Sudbury A. A model for spatial conflict. Biometrika. 1973; 60: 581–588. https://doi.org/10. 2307/2335008

11. Holley RA, Liggett TM. Ergodic theorems for weakly interacting infinite systems and the voter model. Ann Probab. 1975; 3: 643–663. https://doi.org/10.1214/aop/1176996306

12. Liggett TM. Stochastic interacting systems: contact, voter and exclusion processes. Berlin: Springer; 1999.

13. Stark H-U, Tessone CJ, Schweitzer F. Decelerating microdynamics can accelerate macrodynamics in the voter model. Phys Rev Lett. 2008; 101: 018701. https://doi.org/10.1103/PhysRevLett.101.018701 PMID: 18764160

14. Castellano C, Fortunato S, Loreto V. Statistical physics of social dynamics. Rev Mod Phys. 2009; 81: 591–646. https://doi.org/10.1103/RevModPhys.81.591

15. Hayes AF. Exploring the forms of self-censorship: on the spiral of silence and the use of opinion expression avoidance strategies. J Commun. 2007; 57: 785–802. https://doi.org/10.1111/j.1460-2466.2007. 00368.x

16. Lazarsfeld PF, Berelson B, Gaudet H. The people's choice: how the voter makes up his mind in a presidential campaign. New York: Columbia University Press; 1948.

17. Berelson BR, Lazarsfeld PF, McPhee WN. Voting: a study of opinion formation in a presidential campaign. Chicago: University of Chicago Press; 1954.

18. Lang K, Lang GE. Off the bandwagon: some reflections on the influence of perceived public opinion. Individuality and social control: essays in honor of Tamotsu Shibutani. Greenwich, Conn.: JAI Press; 1996.

19. Letenyei L, Takács K. Az előzetes esélyek önerősítő vagy öncáfoló szerepe. Elemzés kísérletek és köz-vélemény-kutatási adatok segítségével. In: Angelusz R, Tardos R, editors. Mérésről mérésre A választáskutatás módszertani kérdései. Budapest: Demokrácia Kutatások Magyar Központja; 2006. pp. 293–314.

20. Davison WP. The public opinion process. Public Opin Q. 1958; 22: 91–106. https://doi.org/10.1086/ 266770

21. Nederhof AJ. Methods of coping with social desirability bias: a review. Eur J Soc Psychol. 1985; 15: 263–280. https://doi.org/10.1002/ejsp.2420150303

22. Grimm P. Social desirability bias. In: Sheth J, Malhotra N, editors. Wiley International Encyclopedia of Marketing. Chichester: Wiley; 2010. https://doi.org/10.1002/9781444316568.wiem02057

23. Krumpal I. Determinants of social desirability bias in sensitive surveys: a literature review. Qual Quant. 2013; 47: 2025–2047. https://doi.org/10.1007/s11135-011-9640-9

24. Myers DG, Bruggink JB, Kersting RC, Schlosser BA. Does learning others' opinions change one's opinions? Pers Soc Psychol Bull. 1980; 6: 253–260. https://doi.org/10.1177/014616728062011

25. Hebert JR, Clemow L, Pbert L, Ockene IS, Ockene JK. Social desirability bias in dietary self-report may compromise the validity of dietary intake measures. Int J Epidemiol. 1995; 24: 389–398. https://doi.org/ 10.1093/ije/24.2.389 PMID: 7635601

26. Press JE, Townsley E. Wives' and husbands' housework reporting: gender, class, and social desirability. Gend Soc. 1998; 12: 188–218. https://doi.org/10.1177/089124398012002005

27. Kamo Y. "He said, she said": assessing discrepancies in husbands' and wives' reports on the division of household labor. Soc Sci Res. 2000; 29: 459–476. https://doi.org/10.1006/ssre.2000.0674

28. Adams SA, Matthews CE, Ebbeling CB, Moore CG, Cunningham JE, Fulton J, et al. The effect of social desirability and social approval on self-reports of physical activity. Am J Epidemiol. 2005; 161: 389–398. https://doi.org/10.1093/aje/kwi054 PMID: 15692083

29. Asch SE. Opinions and social pressure. Sci Am. 1955; 193: 31–35. https://doi.org/10.1038/ scientificamerican1155-31

30. Haun DBM, Tomasello M. Conformity to peer pressure in preschool children. Child Dev. 2011; 82: 1759–1767. https://doi.org/10.1111/j.1467-8624.2011.01666.x PMID: 22023172

31. Bandura A. Selective activation and disengagement of moral control. J Soc Issues. 1990; 46: 27–46. https://doi.org/10.1111/j.1540-4560.1990.tb00270.x

32. Bandura A, Barbaranelli C, Caprara GV, Pastorelli C. Mechanisms of moral disengagement in the exercise of moral agency. J Pers Soc Psychol. 1996; 71: 364–374. https://doi.org/10.1037/0022-3514.71.2.364

33. Valdesolo P, DeSteno D. Moral hypocrisy: social groups and the flexibility of virtue. Psychol Sci. 2007; 18: 689–690. https://doi.org/10.1111/j.1467-9280.2007.01961.x PMID: 17680939

34. Noelle-Neumann E. The spiral of silence a theory of public opinion. J Commun. 1974; 24: 43–51. https://doi.org/10.1111/j.1460-2466.1974.tb00367.x

35. Kuran T. Private truths, public lies: the social consequences of preference falsification. Cambridge, Mass: Harvard University Press; 1995.

36. Jiang J, Yang DL. Lying or believing? Measuring preference falsification from a political purge in China. Comp Polit Stud. 2016; 49: 600–634. https://doi.org/10.1177/0010414015626450

37. Centola D, Willer R, Macy M. The emperor's dilemma: a computational model of self-enforcing norms. Am J Sociol. 2005; 110: 1009–1040. https://doi.org/10.1086/427321

38. Willer R, Kuwabara K, Macy MW. The false enforcement of unpopular norms. Am J Sociol. 2009; 115: 451–490. https://doi.org/10.1086/599250 PMID: 20614762

39. Prentice DA, Miller DT. Pluralistic ignorance and alcohol use on campus: some consequences of misperceiving the social norm. J Pers Soc Psychol. 1993; 64: 243–256. https://doi.org/10.1037/0022-3514.64.2.243 PMID: 8433272

40. Brunsson N. The organization of hypocrisy: talk, decisions, and actions in organizations. Chichester: Wiley; 1989.

41. Wagner T, Lutz RJ, Weitz BA. Corporate hypocrisy: overcoming the threat of inconsistent corporate social responsibility perceptions. J Mark. 2009; 73: 77–91. https://doi.org/10.1509/jmkg.73.6.77

42. Ellinas C, Allan N, Johansson A. Dynamics of organizational culture: individual beliefs vs. social conformity. PLOS ONE. 2017; 12: e0180193. https://doi.org/10.1371/journal.pone.0180193 PMID: 28665960

43. Hughes G. Political correctness: a history of semantics and culture. 1st edition. Maldon, Mass: Wiley-Blackwell; 2009.

44. Noelle-Neumann E. Turbulences in the climate of opinion: methodological applications of the spiral of silence theory. Public Opin Q. 1977; 41: 143–158. https://doi.org/10.1086/268371

45. Festinger L. A theory of cognitive dissonance. Stanford: Stanford University Press; 1962.

46. Kelman HC. Processes of opinion change. Public Opin Q. 1961; 25: 57–78. https://doi.org/10.1086/266996

47. Sherif M. The psychology of social norms. New York and London: Harper & Brothers; 1936.

48. Sherif M and Sherif CW. Groups in harmony and tension. An integration of studies on ontergroup relations. Harper & Brothers; 1953.

49. Crandall CS, Eshleman A, O'Brien L. Social norms and the expression and suppression of prejudice: the struggle for internalization. J Pers Soc Psychol. 2002; 82: 359–378. PMID: 11902622

50. Turner JC, Hogg MA, Oakes PJ, Reicher SD, Wetherell MS. Rediscovering the social group: a self-categorization theory. Cambridge, MA, US: Basil Blackwell; 1987.

51. Galam S, Moscovici S. Towards a theory of collective phenomena: consensus and attitude changes in groups. Eur J Soc Psychol. 1991; 21: 49–74. https://doi.org/10.1002/ejsp.2420210105

52. Ekman P. Should we call it expression or communication? Innov Eur J Soc Sci Res. 1997; 10: 333–344. https://doi.org/10.1080/13511610.1997.9968538

53. Gastner MT, Oborny B, Gulyás M. Consensus time in a voter model with concealed and publicly expressed opinions. J Stat Mech Theory Exp. 2018; 2018: 063401. https://doi.org/10.1088/1742-5468/aac14a

54. Vazquez F, Redner S. Ultimate fate of constrained voters. J Phys Math Gen. 2004; 37: 8479. https://doi.org/10.1088/0305-4470/37/35/006

55. Lambiotte R, Redner S. Dynamics of vacillating voters. J Stat Mech Theory Exp. 2007; 2007: L10001. https://doi.org/10.1088/1742-5468/2007/10/L10001

56. Mobilia M, Georgiev IT. Voting and catalytic processes with inhomogeneities. Phys Rev E. 2005; 71: 046102. https://doi.org/10.1103/PhysRevE.71.046102 PMID: 15903721

57. Mobilia M, Petersen A, Redner S. On the role of zealotry in the voter model. J Stat Mech Theory Exp. 2007; 2007: P08029. https://doi.org/10.1088/1742-5468/2007/08/P08029

58. Sood V, Antal T, Redner S. Voter models on heterogeneous networks. Phys Rev E. 2008; 77: 041121. https://doi.org/10.1103/PhysRevE.77.041121 PMID: 18517592

59. Masuda N, Gibert N, Redner S. Heterogeneous voter models. Phys Rev E. 2010; 82: 010103. https://doi.org/10.1103/PhysRevE.82.010103 PMID: 20866551

60. Masuda N, Redner S. Can partisan voting lead to truth? J Stat Mech Theory Exp. 2011; 2011: L02002. https://doi.org/10.1088/1742-5468/2011/02/L02002

61. Ye M, Qin Y, Govaert A, Anderson BDO, Cao M. An influence network model to study discrepancies in expressed and private opinions. ArXiv180611236 Cs Math. 2018; Available: http://arxiv.org/abs/1806.11236

62. Huang C-Y, Wen T-H. A novel private attitude and public opinion dynamics model for simulating pluralistic ignorance and minority influence. J Artif Soc Soc Simul. 2014; 17: 8.

63. Diakonova M, San Miguel M, Eguíluz VM. Absorbing and shattered fragmentation transitions in multilayer coevolution. Phys Rev E. 2014; 89: 062818. https://doi.org/10.1103/PhysRevE.89.062818 PMID: 25019844

64. Chmiel A, Sznajd-Weron K. Phase transitions in the q-voter model with noise on a duplex clique. Phys Rev E. 2015; 92: 052812. https://doi.org/10.1103/PhysRevE.92.052812 PMID: 26651749

65. Diakonova M, Nicosia V, Latora V, Miguel MS. Irreducibility of multilayer network dynamics: the case of the voter model. New J Phys. 2016; 18: 023010. https://doi.org/10.1088/1367-2630/18/2/023010

66. Klimek P, Diakonova M, Eguíluz VM, Miguel MS, Thurner S. Dynamical origins of the community structure of an online multi-layer society. New J Phys. 2016; 18: 083045. https://doi.org/10.1088/1367-2630/18/8/083045

67. Battiston F, Nicosia V, Latora V, Miguel MS. Layered social influence promotes multiculturality in the Axelrod model. Sci Rep. 2017; 7: 1809. https://doi.org/10.1038/s41598-017-02040-4 PMID: 28500281

68. Redner S. A guide to first-passage processes. 1st edition. Cambridge, UK: Cambridge University Press; 2001.

69. Gillespie DT. Exact stochastic simulation of coupled chemical reactions. J Phys Chem. 1977; 81: 2340–2361. https://doi.org/10.1021/j100540a008

70. Gastner MT. Source code for simulations presented in "The impact of hypocrisy on opinion formation: a dynamic model": mgastner/impact-of-hypocrisy [Internet]. 2018. Available: https://github.com/mgastner/impact-of-hypocrisy

71. Ángeles Serrano M, Klemm K, Vazquez F, Eguíluz VM, San Miguel M. Conservation laws for voter-like models on random directed networks. J Stat Mech Theory Exp. 2009; 2009: P10024. https://doi.org/10.1088/1742-5468/2009/10/P10024

72. Davis JH, Hulbert L, Au WT, Chen X, Zarnoth P. Effects of group size and procedural influence on consensual judgments of quantity: the examples of damage awards and mock civil juries. J Pers Soc Psychol. 1997; 73: 703–718. https://doi.org/10.1037/0022-3514.73.4.703

73. Saks MJ. What do jury experiments tell us about how juries (should) make decisions. South Calif Interdiscip Law J. 1997; 6: 1.

74. Saks MJ, Marti MW. A meta-analysis of the effects of jury size. Law Hum Behav. 1997; 21: 451–467. https://doi.org/10.1023/a:1024819605652

75. Waters NL, Hans VP. A jury of one: opinion formation, conformity, and dissent on juries. J Empir Leg Stud. 2009; 6: 513–540. https://doi.org/10.1111/j.1740-1461.2009.01152.x

76. Devine DJ, Clayton LD, Dunford BB, Seying R, Pryce J. Jury decision making: 45 years of empirical research on deliberating groups. Psychol Public Policy Law. 2001; 7: 622–727. https://doi.org/10.1037/1076-8971.7.3.622

77. Katz D. The functional approach to the study of attitudes. Public Opin Q. 1960; 24: 163–204. https://doi.org/10.1086/266945

78. Kelman HC. Processes of opinion change. Public Opin Q. 1961; 25: 57–78. https://doi.org/10.1086/266996

79. Maass A, Clark RD. Internalization versus compliance: differential processes underlying minority influence and conformity. Eur J Soc Psychol. 1983; 13: 197–215. https://doi.org/10.1002/ejsp.2420130302

80. Galam S, Jacobs F. The role of inflexible minorities in the breaking of democratic opinion dynamics. Phys Stat Mech Its Appl. 2007; 381: 366–376. https://doi.org/10.1016/j.physa.2007.03.034

81. Yildiz E, Ozdaglar A, Acemoglu D, Saberi A, Scaglione A. Binary opinion dynamics with stubborn agents. ACM Trans Econ Comput. 2013; 1: 19:1–19:30. https://doi.org/10.1145/2538508

82. Nemeth C, Wachtler J. Creating the perceptions of consistency and confidence: a necessary condition for minority influence. Sociometry. 1974; 37: 529–540. https://doi.org/10.2307/2786425

83. Paicheler G. Norms and attitude change I: polarization and styles of behaviour. Eur J Soc Psychol. 1976; 6: 405–427. https://doi.org/10.1002/ejsp.2420060402

84. Maass A, Clark RD, Haberkorn G. The effects of differential ascribed category membership and norms on minority influence. Eur J Soc Psychol. 1982; 12: 89–104. https://doi.org/10.1002/ejsp.2420120107

85. Amblard F, Deffuant G. The role of network topology on extremism propagation with the relative agreement opinion dynamics. Phys Stat Mech Its Appl. 2004; 343: 725–738. https://doi.org/10.1016/j.physa.2004.06.102

86. Axelrod R. The dissemination of culture: a model with local convergence and global polarization. J Confl Resolut. 1997; 41: 203–226. https://doi.org/10.1177/0022002797041002001

87. Carley K. A theory of group stability. Am Sociol Rev. 1991; 56: 331–354. https://doi.org/10.2307/2096108

88. Mark N. Beyond individual differences: social differentiation from first principles. Am Sociol Rev. 1998; 63: 309–330. https://doi.org/10.2307/2657552

89. Tsuji R. Interpersonal influence and attitude change toward conformity in small groups: A social psychological model. J Math Sociol. 2002; 26: 17–34. https://doi.org/10.1080/00222500210528

90. Mark NP. Culture and competition: homophily and distancing explanations for cultural niches. Am Sociol Rev. 2003; 68: 319–345. https://doi.org/10.2307/1519727

91. Flache A, Mäs M, Feliciani T, Chattoe-Brown E, Deffuant G, Huet S, et al. Models of social influence: towards the next frontiers. J Artif Soc Soc Simul. 2017; 20: 2.

92. Quattrociocchi W, Caldarelli G, Scala A. Opinion dynamics on interacting networks: media competition and social influence. Sci Rep. 2014; 4: 4938. https://doi.org/10.1038/srep04938 PMID: 24861995

93. Mckeown G, Sheehy N. Mass media and polarisation processes in the bounded confidence model of opinion dynamics. J Artif Soc Soc Simul. 2006; 9: 11.

94. Martins TV, Pineda M, Toral R. Mass media and repulsive interactions in continuous-opinion dynamics. EPL Europhys Lett. 2010; 91: 48003. https://doi.org/10.1209/0295-5075/91/48003

95. Simmel G. Fashion. Am J Sociol. 1957; 62: 541–558.

96. Turchin P. Dynamics of political instability in the United States, 1780–2010. J Peace Res. 2012; 49: 577–591. https://doi.org/10.1177/0022343312442078