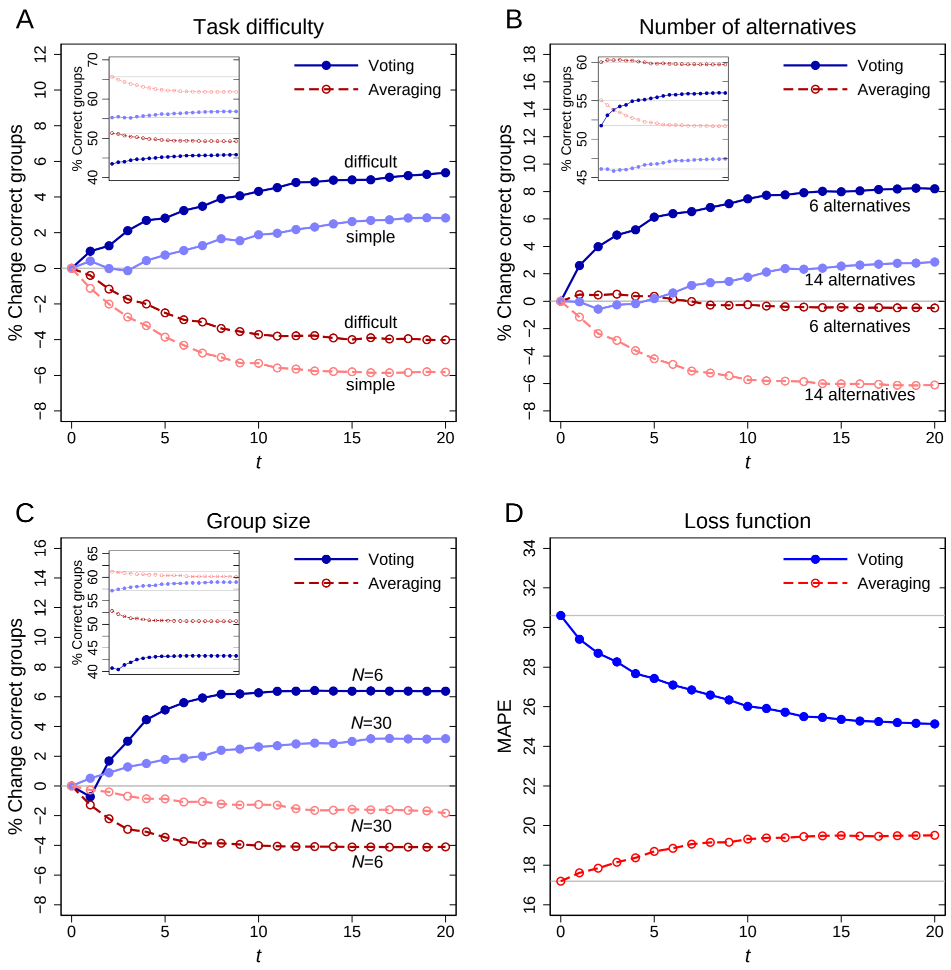

Fig. 5. Variations of the task environment. Our overall result generalizes to different (**A**) task difficulties, (**B**) numbers of alternatives, and (**C**) group sizes as well as to a continuous loss function (**D**). For the latter result, we calculate collective accuracy as a group's mean absolute percentage error (MAPE), which equals the absolute percentage difference between the best alternative's criterion value and the chosen alternative's value. Insets show the shares of correct groups over interaction rounds t.

relative improvements in collective accuracy under voting are most pronounced for social learning in a difficult task environment: After 20 rounds of dyadic interaction, the share of accurate groups increased by 5.4% for a difficult task, whereas the increase is 2.8% for a simple task. For averaging, in contrast, relative losses through social influence are largest in simple tasks, for which, at the end of our simulation, we encounter 5.8% less correct groups (as opposed to –4.0% for difficult tasks). The inset now indicates the percentage-point change in correct group solutions over rounds t.

- In Fig. 5B, we vary the number of alternatives from which the agents have to choose. We test K=6 and K=14. This manipulation, again, moderates social-influence effects differently for each aggregation rule: Under a limited choice set, social-influence effects reduce for averaging (–0.5% correct groups) but increase for voting (+8.2% correct groups). Effect sizes revert for a larger choice set. Still, our overall result—according to which social influence strengthens crowd wisdom under voting—remains robust.
- In Fig. 5C, we vary group sizes. Voting gains more from social influence in smaller (N=6) than in larger groups (N=30). Similarly, losses under averaging are smaller for large than for small groups. Collective accuracy crucially depends on the size of crowds (see inset), and group size is particularly important for voting. Note that for N=30 collective accuracy for interacting voters almost catches up to levels found for averaging: After 20 rounds of dyadic interaction, the share of accurate groups differs between aggregation rules by only 1.1 percentage points (see inset). This catch-up, again, stands in stark contrast to conventional knowledge, stressing the negative consequences of social influence on crowd wisdom altogether.
- In Fig. 5D, we replicate our finding based on a continuous loss function. We chose mean absolute percentage error (MAPE), which equals the absolute percentage difference between the best alternative's criterion value and the chosen alternative's value. The scale-independent measure is canonical in the forecasting literature [48, 49]. MAPE increases over interaction rounds for averaging but decreases for voting. Our original result is thus independent of the specific loss function employed.

Second, relying on established social-science findings on humans' adaptive behavior, we introduce alternative variants of social influence for generalizability. For each manipulation, our overall result remains robust (Fig. 6). These sensitivity analyses also demonstrate that our main result can be obtained without homophily (Fig. 6B) and asymmetric influence (Fig. 6C).

- In Fig. 6A, we manipulate assignments of agents' confidence. Humans typically overestimate their own abilities and, in the framework of opinion dynamics, put higher weights on their own initial opinions. We implement "overconfidence" [50, 51] using a relative increase of ego's actual confidence s_i over the perceived confidence of alter s_j. The rules of asymmetric influence for an overconfident agent thus change according to Tab. 3. Our implementation of overconfidence reduces agents' readiness for social learning such that agents react only to relatively more confident others. Because signals of others' confidence remain valid, overconfidence accelerates the positive social-influence effect under voting. By a similar mechanism, overconfidence attenuates the negative consequences of social influence under averaging. Results change, however, if confidence signals lose validity (see

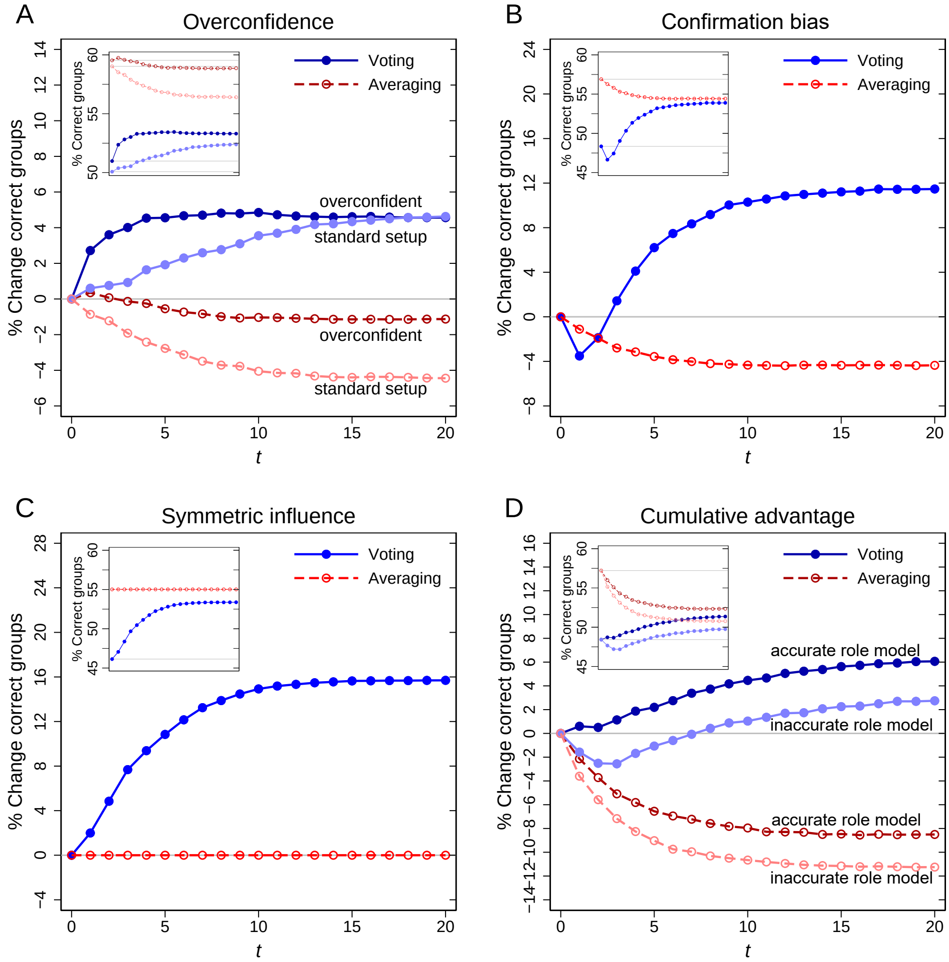

Fig. 6. Variations of the social-influence regime. Our overall result remains robust to the introduction of (**A**) overconfidence (see Tab. 3 for the respective rules of advice-taking), (**B**) the substitution of closeness of opinions for our specification of homophily, (**C**) symmetric instead of asymmetric influence, and (**D**) cumulative advantage in advice-taking. In the latter specification, we endogenize the attractiveness of others' advice by conditioning the formation of beliefs about alteri's confidence on their popularity as a role model. Consequently, the influence of some group members over a groups' aggregated judgment increases in interaction rounds t (accurate = a group's best member; inaccurate = a group's worst member). Insets show the shares of correct groups over interaction rounds t.

Fig. 7*A*).

- In Fig. 6*B*, we substitute closeness of opinions for our specification of homophily. Individuals seek and interpret evidence in ways that are partial to existing beliefs. We include "confirmation bias" [38, 39] by restricting

Table 3. Rules for asymmetric influence with overconfidence. Agents weigh advice according to beliefs about their own and others' predictive ability s. Agent i adopts interaction partner j's estimates if $s_i << s_j$ (a); i and j compromise if $s_i < s_j$ (c); i keeps her original judgments if $s_i \geq s_j$ (k). Adoptions and compromises are less likely due to overconfidence.

		Alter j's confidence s		
		low	medium	high
	low	k,k	c,k	a,k
Ego i	medium	k,c	k,k	c,k
	high	k,a	k,c	k,k

social influence to others whose judgments are close to the agent's own. This specification of selective influence is equivalent to the original formulation of the Deffuant model [29]. Besides this manipulation, we maintain our implementation of asymmetric influence according to Tab. 1. After 20 rounds of dyadic interaction, the share of correct voting groups increases by 11.5%. Under averaging, this fraction drops by 4.4%. In effect, the share of accurate group solutions differs between aggregation rules by only .5 percentage points (see inset).

- In Fig. 6*C*, we implement an inverse manipulation, keeping our original specification of homophily but shutting off asymmetric influence. Now, same-type agents' positions converge regardless of ego's and alter's confidence. Social influence, again, is beneficial for voting outcomes, raising the share of correct groups by 15.7% at the end of our simulation. Under symmetric influence, however, social interaction has zero effect on averaging's performance because a group's average opinion remains invariant to social dynamics (see also footnote c above).
- In Fig. 6*D*, we endogenize others' attraction as role models. Human decision-making often relies on strategies of social proof [52, 53], particularly in situations of uncertainty. An agent may confide in another only if she has served as a role model for others. We include "cumulative advantage" [54, 55] by conditioning the formation of beliefs about alteri's confidence on their popularity as a role model: The more agents followed j, the higher i's perception of j's predictive accuracy. As a consequence, j's influence over a groups' aggregated judgment increases in t. Keeping our standard setup except for this implementation of cumulative advantage, we find that social-influence effects crucially depend on the predictive ability of focal others. If role models exhibit high predictive ability (we equipped each group's best member with an individual advantage), social-influence effects remain at the level of our standard setup: After 20 rounds of dyadic interaction, the share of correct groups increases by 6.1% under voting but

decreases by 8.5% under averaging. If role models instead lack accuracy (we seeded each group's worst member), aggregated judgment deteriorates: At the end of our simulation, correct group solutions increase by 2.7% under voting and decrease by 11.2% under averaging. Importantly for our argument, voting still benefits from social influence even when role models bolstered by cumulative advantage lack predictive ability.

Concluding this section, we identify the boundary conditions under which our overall result vanishes and social influence also becomes detrimental to crowd wisdom under voting. This is the case if we change our confidence measure to correlate negatively with actual predictive accuracy or if social influence no longer depends upon argument exchange but reduces to purely observational learning.

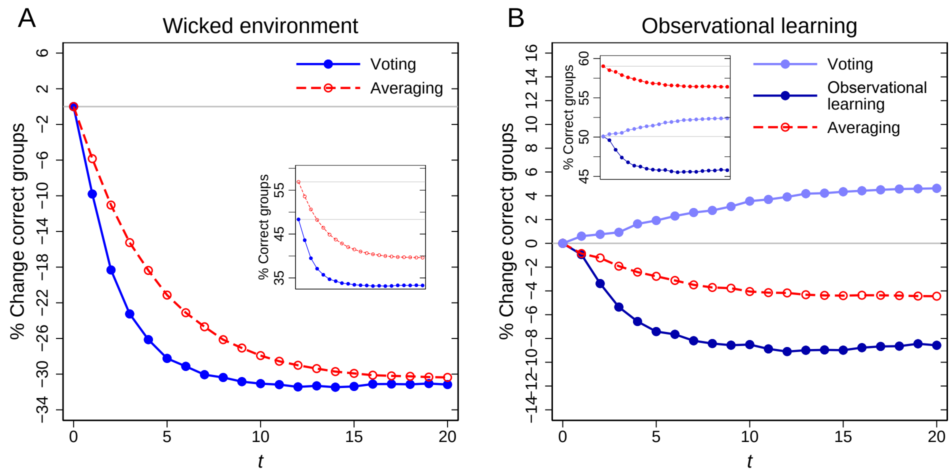

Fig. 7. Boundary conditions. (**A**) In a wicked environment, agents' beliefs in their own and in others' predictive abilities correlate negatively with actual performance ($\rho = -.8$). Consequently, agents misjudge their own and others' predictive abilities and aggregated judgment suffers under both averaging and voting. (**B**) Observational learning conveys less information than argument exchange, and positive social-influence effects on voting outcomes reverse in an observable-actions-scenario. Insets show the shares of correct groups over interaction rounds t.

Confidence is misleading if we substitute a "kind" for a "wicked" environment [47]. In a wicked environment, agents' beliefs in their own and in others' predictive abilities no longer correlate positively with actual performance. We thus leave a transparent state of nature, in which ability has been observable, for a non-meritocratic world in which perceived confidence ceases to indicate actual ability. Technically, s now correlates with actual predictive accuracy at $\rho = -.8$, reflecting novel judgment problems in which past experience is of little help, others' predictive ability is highly opaque, or social status feeds on other sources than individual ability. In consequence, agents misjudge their own capabilities to come up with appropriate judgments and, at the same time, follow the wrong leaders. Fig. 7*A* summarizes the concomitant negative effects of social influence for aggregated judgment under both averaging and voting. After 20 rounds of dyadic interaction, the share of accurate groups decreased by 31.2% under voting, and only 33.3% of groups return a correct solution (see inset). This rate similarly drops by 30.4% for averaging, leaving 39.6% of groups with a correct solution. Recall that 37.7% of our agents find the correct solution autonomously. In absolute terms, social influence in a wicked environment thus inhibits crowd wisdom in discrete choice tasks but spares a small advantage for continuous estimation tasks.

So far, we modeled social influence based on exchanges of arguments (i.e. the revealing of private signals $\hat{Q}_i$ and $\hat{Q}_j$). Many group decisions, however, do not allow for argument exchange, and many agents lack enough motivation to share private information. In these instances, agents have to rely on observable actions V_j for social learning. Because actions convey less information than private signals, such social-influence regimes are prone to herd behavior [19, 56]. As a result, positive social-influence effects on voting outcomes cease under an observable-actions regime (Fig. 7*B*). Now, social influence—just as under averaging—leads to lowered collective accuracy. Voting's loss to observational learning is substantial, reducing the share of accurate groups by 8.6% at the end of our simulation. This finding is in line with experimental evidence from Frey and van de Rijt [57] indicating that voting groups find correct solutions less frequently if exposed to the popularity of alternatives rather than to others' estimates of intrinsic value. Still, even under observational learning—and unlike the voting performance in a wicked environment—voting groups find correct solutions more frequently (45.8%, see inset) than agents do autonomously (37.7%).

5. Discussion

Our analysis of crowd wisdom reproduces a common finding of modern-day social-choice research: For collective accuracy in truth-tracking tasks, one should seek aggregated judgment using averaging rather than voting [27, 28, 36]. Using cardinal "evaluations" instead of nominal "choices," averaging considers more individual information and, unlike voting, effectively neutralizes over- and underestimations of a criterion. Consequently, in finding accurate group solutions averaging trumps voting. From our inclusion of repeated local interaction among otherwise isolated decision-makers we derive further implications. Adding to our knowledge about complex systems comprised of adaptive agents, these findings have important ramifications for designing collective decision-making in both public administration and private firms.

To benefit from error cancellation under averaging, individual judgments are best taken in isolation. The independence requirement for predictions on a metric scale is a strong argument against the use of group discussions or interactive expert panels for aggregated judgment. Although social influence allows for individual learning, improved accuracy at the individual level in our simulations could not compensate for the group-level loss in predictive diversity. We do not claim originality in this result, which a series of laboratory studies [14, 15, 24] have addressed. Instead, we used it as a benchmark to evaluate social-influence effects on voting outcomes.

While our analysis demonstrates that averaging always trumps voting, even after social learning, our primary concern lies in finding strategies that improve outcomes of voting, the single most-important social decision rule in modern society. Voting's relative disadvantage to averaging minimizes under social influence. By granting agents the opportunity to revise their initial judgments and thereby converge on others' opinions, assimilative social influence transports the power of the averaging principle into discrete choice tasks. As a result—depending on the specific parameter setting—collective accuracy under voting can approach levels almost as high as under averaging. Hence, if forced to ubiquitous voting—which is often the case in committees in both firms and public administrations—decision-makers should receive opportunities to exchange their views and opinions, allowing each individual to interact with as many others as possible. Against the fact that averaging sees little use as an aggregation rule in practice, the widespread overgeneralization of negative social-influence effects on crowd wisdom is thus surprising.

There are, however, important boundary conditions to our finding. For social influence to strengthen voting outcomes, both transparency of others' predictive ability as well as the actual exchange of arguments proves highly relevant. On the one hand, agents must receive precise perceptions as to the basis of their interaction partners' confidence. Agents' following the wrong leaders offsets the benefits of social influence. On the other hand, social influence adds to information aggregation only if agents exchange opinions rather than merely follow others' votes. A breakdown to purely observational learning considers less individual information and is prone to herd behavior. Consequently, we found a dramatic decrease in collective accuracy in an observable-action scenario.

Collective decision-making thus needs careful design, a general insight that relates our analysis to structured approaches to the aggregation of diverse opinions within expert groups [58–60]. Focusing on truth-tracking, we took an epistemic perspective on group consensus [32–34] but left out important facets of social life, such as individual preferences, strategic interaction, group polarization, and specific network topologies [61–64]. Integrating those into the study of crowd wisdom under voting is open to future research.

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References

[1] Larson, J. R., *In Search of Synergy in Small Group Performance* (Psychology Press, New York, 2010).
[2] Galton, F., Vox populi. *Nature* **75** (1907) 450-451.
[3] Hong, L. and Page, S. E., Groups of diverse problem solvers can outperform groups of high-ability problem solvers. *Proc. Natl. Acad. Sci. USA* **101** (2004) 16385-16389.
[4] Larrick, R.P. and Soll, J. B., Intuitions about combining opinions: Misappreciation of the averaging principle. *Manage. Sci.* **52** (2006) 111-127.
[5] Bonabeau, E., Dorigo, M., and Theraulaz, G., *Swarm Intelligence: From Natural to Artificial Systems* (Oxford University Press, New York, 1999).
[6] Krause, J., Ruxton, G. D., and Krause, S., Swarm intelligence in animals and humans. *Trends Ecol. Evol.* **25** (2010) 28-34.
[7] Surowiecki, J., *The Wisdom of Crowds: Why the Many Are Smarter than the Few and How Collective Wisdom Shapes Business, Economies, Societies, and Nations* (Doubleday Books, New York, 2004).
[8] Page, S. E., *The Difference: How the Power of Diversity Creates Better Groups, Firms, Schools, and Societies* (Princeton University Press, Princeton, 2007).
[9] Hogarth, R. M., A note on aggregating opinions. *Organ. Behav. Human. Perform.* **21** (1978) 40-46.
[10] Grofman, B., Owen, G., and Feld, S. L., Thirteen theorems in search of the truth. *Theor. Decis.* **15** (1983) 261-278.
[11] Abelson, R. P., Mathematical models of the distribution of attitudes under controversy, in *Contributions to Mathematical Psychology*, eds. Frederiksen, N. and Gulliksen, H. (Rinehart Winston, New York, 1964) pp 142-160.
[12] DeGroot, M. H., Reaching a consensus. *J. Am. Stat. Assoc.* **69** (1974) 118-121.
[13] Flache, A., Mäs, M., Feliciani, T., Chattoe-Brown, E., Deffuant, G., Huet, S., and Lorenz, J., Models of social influence: Towards the next frontiers. *J. Artif. Soc. Soc. Simulat.* **20** (2017) 2.
[14] Lorenz, J., Rauhut, H., Schweitzer, F., and Helbing, D., How social influence can undermine the wisdom of crowd effect. *Proc. Natl. Acad. Sci. USA* **108** (2011) 9020-9025.
[15] Moussaïd, M., Kämmer, J. E., Analytis, P. P., and Neth, H. Social influence and the collective dynamics of opinion formation. *PLoS ONE* **8** (2013) e78433.
[16] Janis, I. L., *Victims of Groupthink: A Psychological Study of Foreign-Policy Decisions and Fiascoes* (Houghton Mifflin, Oxford, 1972).
[17] Sunstein, C., *Going to Extremes: How Like Minds Unite and Divide* (Oxford University Press, New York, 2009).
[18] Mackay, C., *Extraordinary Popular Delusions and the Madness of Crowds* (Bentley, London, 1841).
[19] Bikhchandani, S., Hirshleifer, D., and Welch, I., A theory of fads, fashion, custom, and cultural change as informational cascades. *J. Polit. Econ.* **100** (1992) 992-1026.
[20] Schelling, T. C., Dynamic models of segregation. *J. Math. Sociol.* **1** (1971) 143-186.
[21] King, A. J., Cheng, L., Starke. S. D., and Myatt, J. P., Is the true 'wisdom of the crowd' to copy successful individuals? *Biol. Lett.* **8** (2012) 197200.
[22] Madirolas, G., de Polavieja, G. G., Improving collective estimations using resistance

to social influence. *PLoS Comput. Biol.* **11** (2015) e1004594.

[23] Mavrodiev, P., Tessone, C. J., Schweitzer, F., Effects of social influence on the wisdom of crowds. arXiv:1204.3463 (2012).

[24] Becker, J., Brackbill, D., and Centola, D. Network dynamics of social influence in the wisdom of crowds. *Proc. Natl. Acad. Sci. USA* **114** (2017) E5070-E5076.

[25] Jayles, B., Kim, H., Escobedo, R., Cezera, S., Blanchet, A., Kameda, T., Sire, C., and Theraulaz, G., How social information can improve estimation accuracy in human groups. *Proc. Natl. Acad. Sci. USA* **114** (2017) 12620-12625.

[26] Condorcet, J. A. N., *Essai sur l'Application de l'Analyse à la Probabilité des Décisions Rendues à la Pluralité des Voix* (Imprimerie Royale, Paris, 1785).

[27] Balinski, M. and Laraki, R., *Majority Judgment: Measuring, Ranking, and Electing* (MIT Press, Cambridge, 2010).

[28] Hastie, R. and Kameda, T., The robust beauty of majority rules in group decisions. *Psychol. Rev.* **112** (2005) 494-508.

[29] Deffuant, G., Neau, D., Amblard, F., and Weisbuch, G., Mixing beliefs among interacting agents. *Adv. Complex Syst.* **3** (2000) 87-98.

[30] Hegselmann, R. and Krause, U., Opinion dynamics and bounded confidence models, analysis, and simulation. *J. Artif. Soc. Soc. Simul. 5* (2002).

[31] Castellano, C., Fortunato, S., and Loreto, V., Statistical physics of social dynamics. *Rev. Mod. Phys.* **81** (2009) 591-646

[32] Estlund, D. M., Democracy without preference. *Philos. Rev.* **49** (1990) 397-424.

[33] Grofman, B. and Feld, S. L., Rousseau's general will: A Condorcetian perspective. *Am. Polit. Sci. Rev.* **82** (1988) 567-576.

[34] List, C. and Goodin, R. E., Epistemic democracy: Generalizing the Condorcet jury theorem. *J. Polit. Philos.* **9** (2001) 277-306.

[35] Brunswik, E., Representative design and probabilistic theory in a functional psychology. *Psychol. Rev.* **62** (1955) 193-217.

[36] Keuschnigg, M. and Ganser, C., Crowd wisdom relies on agents' ability in small groups with a voting aggregation rule. *Manage. Sci.* **63** (2017) 818-828.

[37] Karelaia, N. and Hogarth, R. M., Determinants of linear judgment: A meta-analysis of lens model studies. *Psychol. Bull.* **134** (2008) 404-426.

[38] Lord, C. G., Ross, L., and Lepper, M. R., Biased assimilation and attitude polarization: The effects of prior theories on subsequently considered evidence. *J. Pers. Soc. Psychol.* **37** (1979) 2098-2109.

[39] Nickerson, R. S., Confirmation bias: A ubiquitous phenomenon in many guises. *Rev. Gen. Psychol.* **2** (1998) 175-220.

[40] Lazarsfeld, P. F. and Merton, R. K., Friendship as a social process: a substantive and methodological analysis, in *Freedom and Control in Modern Society*, ed. Berger, M. (Van Nostrand, New York, 1954), pp 18-66.

[41] McPherson, M., Smith-Lovin, L., and Cook, J. M., Birds of a feather: Homophily in social networks. *Annu. Rev. Sociol.* **27** (2001) 415-444.

[42] Latané, B., The psychology of social impact. *Am. Psychol.* **36** (1981) 343-356.

[43] Yaniv, I., Receiving other people's advice: influence and benefit. *Organ. Behav. Hum. Decis. Process.* **93** (2004) 1-13.

[44] Soll, J. B. and Larrick, R. P., Strategies for revising judgment: how (and how well) people use others' opinions. *J. Exp. Psychol. Learn. Mem. Cogn.* **35** (2009) 780-805.

[45] Birnbaum, M. H. and Stegner, S. E., Source credibility in social judgment: Bias, expertise, and the judge's point of view. *J. Pers. Soc. Psychol.* **37** (1979) 48-74.

[46] Melamed, D. and Savage, S. V., Status, faction sizes, and social influence: Testing the theoretical mechanism. *Am. J. Sociol.* **122** (2016) 201-232.

[47] Hertwig, R., Tapping into the wisdom of the crowd—with confidence. *Science* **336** (2012) 303-304.

[48] Makridakis, S., Accuracy measures: Theoretical and practical concerns. *Int. J. Forecast.* **9** (1993) 527-529.

[49] Hyndman, R. J. and Koehler, A. B., Another look at measures of forecast accuracy. *Int. J. Forecast.* **22** (2006) 679-688.

[50] Kruger, J. and Dunning, D., Unskilled and unaware of it: How difficulties in recognizing one's own incompetence lead to inflated self-assessments. *J. Pers. Soc. Psychol.* **77** (1999) 1121-1134.

[51] Bonaccio, S. and Dalal, R. S., Advice taking and decision-making: An integrative literature review, and implications for the organizational sciences. *Organ. Behav. Hum. Decis. Process.* **101** (2006) 127-151.

[52] Deutsch, M. and Gerard, H. B., A study of normative and informational social influences upon individual judgment. *J. Abnorm. Psychol.* **51** (1955) 629-636.

[53] Cialdini, R. B. and Goldstein, N. J., Social influence: Compliance and conformity. *Annu. Rev. Psychol.* **55** (2004) 591-621.

[54] Merton, R. K., The Matthew effect in science. *Science* **159** (1968) 56-63.

[55] DiPrete, T. A. and Eirich, G. M., Cumulative advantage as a mechanism for inequality: A review of theoretical and empirical developments. *Annu. Rev. Sociol.* **32** (2006) 271-297.

[56] Chamley, C. P., *Rational Herds: Economic Models of Social Herding* (Cambridge University Press, Cambridge, 2004).

[57] Frey, V. and van de Rijt, A., Social influence undermines the crowd in sequential decision-making. Utrecht University (2018).

[58] Dalkey, N. and Helmer, O., An experimental application of the Delphi method to the use of experts. *Manage. Sci.* **9** (1963) 458-467.

[59] Aspinall, W., A route to more tractable expert advice. *Nature* **463** (2010) 294-295.

[60] Koriat, A., When are two heads better than one and why? *Science* **336** (2012) 360-362.

[61] Kameda, T., Tsukasaki, T., Hastie R., and Berg, N., Democracy under uncertainty: The wisdom of crowds and the free-rider problem in group decision making. *Psychol. Rev.* **118** (2011) 76-96.

[62] Mäs, M. and Flache, A., Differentiation without distancing: Explaining bi-polarization of opinions without negative influence. *PLoS ONE* **8** e74516.

[63] Del Vicario, M., Scala, A., Caldarelli, G., Stanley, H. E., and Quattrociocchi, W., Modeling confirmation bias and polarization. *Sci. Rep.* **7** (2017) 40391;

[64] Acemoglu, D. and Ozdaglar, A., Opinion dynamics and learning in social networks. *Dyn. Games Appl.* **1** (2011) 3-49.

Appendix

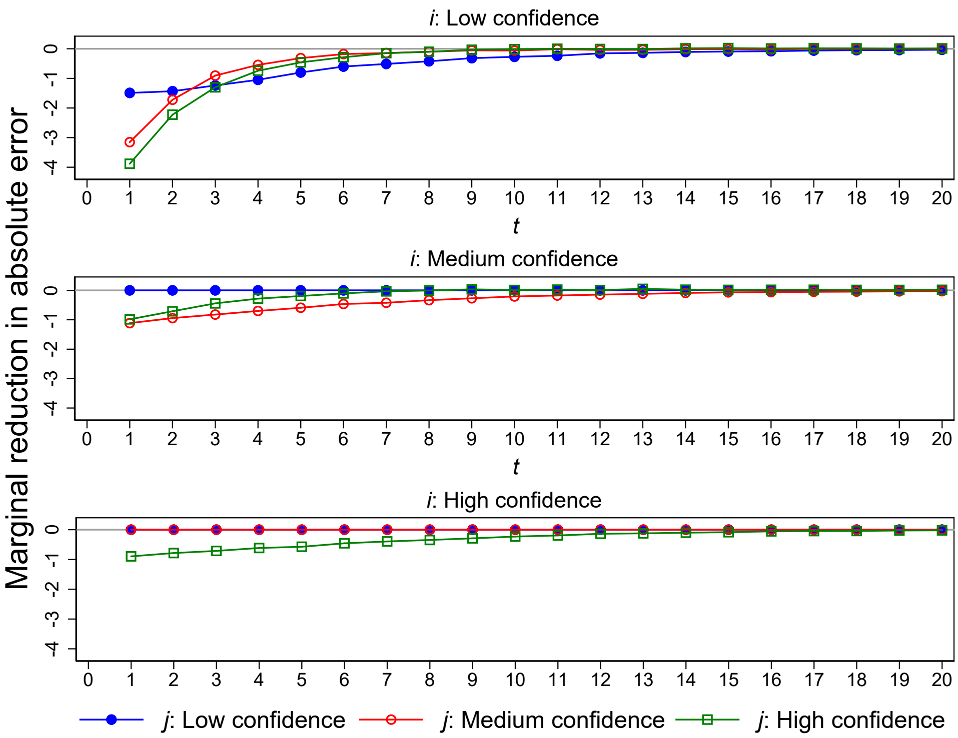

Fig. 8. Marginal reduction in individual error over iterations t. Differentiated by confidence type (low, medium, high) these graphs show i's marginal improvement in precision (t to $t+1$) conditional on the interaction partner j's confidence.