Invited Exchange of Letters

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An exchange of letters on the role of noise in collective intelligence

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A key but neglected issue in the search for collective intelligence principles is the role of noise. Does noise inhibit collective intelligence or can it amplify the discovery of intelligent solutions? In this exchange of letters, the authors explore the pros and cons of noise.

—Jessica Flack, Co-Editor-in-Chief

Benefits of Noise in Collective Systems: the Four-fold way

David C. Krakauer and David Wolpert

Dear Drs. Kahneman, Sibony, and Sunstein,

We read your book and letter with great interest. You make a very compelling case for increasing awareness of the negative consequences of noise, especially in socio-political-economic decision making. This helps to balance all of the attention that has traditionally been paid to issues of bias. Your most convincing arguments relate to the why and how reducing noise leads to improved outcomes across numerous domains of individual human judgment, from medicine to the law.

As we read you, “bias” describes how far a prediction is from the average value of a quantity. The perennial optimist has positive bias, and the incorrigible pessimist has negative bias, but both are biased. “Noise” (or variance, to give it its formal name) captures the scatter around the average prediction. A meteorologist who predicts every day that the temperature will have exactly its average value is unbiased—but their predictions can have a lot of noise.

It might interest you to know that the philosopher Arthur Schopenhauer wrote in 1905 that “the amount of noise that anyone can bear undisturbed stands in inverse proportion to his mental capacity and therefore be regarded as a pretty fair measure of it” (Arthur et al., n.d). In a certain respect, you are channeling Schopenhauer and imploring us to increase our mental capacities.

Your primary point is that if the decisions and or predictions are made by a single person, at a single moment, then noise can be (highly) deleterious. We call such scenarios the domain of individual exploitation. You recognize that there will be situations where noise in one’s decisions

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can be exploited to reduce cost or increase individual freedom. But far more numerous are the situations where noise cannot be exploited and is deleterious. This point is well taken and the community at large should be heedful of developing blind-spots in judgment by exclusive attention to matters of bias.

However, there is another domain in which either a single person is engaged in a time-extended sequence of multiple predictions and decisions, or a set of multiple people are making predictions and decisions together. Let’s call this the domain of collective exploration. In these scenarios, information is derived across an ensemble of individuals and/or moments, and it is rarely a point estimate that is being made but a process that needs to be advanced. In most of these cases, as you most likely would agree, noise is an essential functional requirement. And more often than not, this noisy phase of activity precedes the individual exploitation phase where noise becomes increasingly detrimental.

William James celebrates the benefit of the freedom to explore in his influential paper “The Dilemma of Determinism” where he writes, “Let us not fear to shout it from the house-tops if need be; for we now know that the idea of chance is, at bottom, exactly the same thing as the idea of gift” (James, n.d).

Perhaps the great research challenge moving forward is finding balanced approaches to managing both desirable and undesirable sources of noise. And in order to do so, we need a firmer understanding of collective exploration. As a tentative foray in this direction, we have included a simple figure in order to categorize the space of functional noise in collective systems. We label the vertices of a quadrilateral with problems of Optimization; Computation and Inference; Signal Detection; and Mechanics. In what follows, we provide a very brief introduction to each of these vertices (Figure 1).

Figure 1. The four-fold value of functional noise in collective systems. Functional noise is organized into four categories, and several examples are provided for each. We have in mind a taxonomy of ways that noise can be harnessed to benefit a system without which function at the collective level would be rendered impossible.

In complex optimization problems, utility or fitness functions are typically non-isotropic (multi-peaked), degenerate (many equivalent optima), non-convex, and/or dynamically changing. In these problems, a collection of measurements is made, extending over time and/or space, so as to decide on how to move in a suitable configuration space. In the engineering sciences, these problems of how to behave across a collection of times arise in active learning (Settles, 2012), experimental design (Ryan and Morgan, 2007), optimization theory (Rao, 2019), control theory (Doyle et al., 2013), or reinforcement learning more generally (Sutton and Barto, 2018). Similarly, collective processes in the natural world, like mutation-selection (Charlesworth, 1990), and their engineered analogs including genetic algorithms (Mitchell, 1998), and simulated annealing (Van Laarhoven and Aarts, 1987), employ random perturbations in order to discover paths toward viable solutions within a population of agents collectively exploring a space. Once at global equilibrium, as KSS argue, noise becomes a liability. In population genetics, the associated elimination of noise at a fitness maximum is called the general reduction principle (Altenberg and Feldman, 1987).

Modern collective and distributed forms of computation make extensive use of noise. This includes the very fundamental nature of random processes associated with quantum entanglement and quantum computation (Steane, 2004), the need to operate in the critical regime of collective spins in Ising systems so as to ensure high memory capacity in the Hopfield model (Hopfield, n.d), and the requirement that Boltzmann machines operate in regimes of non-zero temperature/noise (Ackley et al., 1985). Noise is also an essential feature of most modern forms of model-based inference, most notably the principle of maximum entropy, where noise is required for the estimation of constrained Bayesian priors (Jaynes, 1982).

And at the level of mechanical and collective molecular processes, randomness is essential for the construction of stochastic machines including Brownian ratchets (Fornés, 2021) that support contractile forces, mechanisms of stochastic self-assembly in distributed agents (Klavins et al., 2021), cell receptor densification (Shimizu and Bray, 2021), and as a system parameter for modulating ultra-sensitivity required for hysteresis supporting molecular memory and switches in populations of enzymes (Smith et al., 2011). And in large populations of cells classified into tissues, such as heart muscle, noise is essential in maintaining adaptability. The loss of noise in cardiac rhythms leads to a fatal determinism associated with congestive heart failure (Goldberger et al., 2002).

More generally, if we consider a multiplicity of individuals, each optimizing a different objective function which involves the choices of the other players as well as herself, then equilibrium might require noise. The simple
game of “penny-matching” illustrates the point. Suppose there are two individuals (“players”) each of whom can choose heads or tails. Suppose the first player’s objective is maximized when they make the same choice as their opponent, while the second player’s objective is maximized when they make the opposite choice of their opponent. As Nash emphasized, in his Nobel-prize–winning contribution to game theory, the only equilibrium of this penny-matching game, the only way for the players not to get caught in an endless cycle, is for both players to choose heads randomly, with 50% probability (Binmore and Samuelson, 1997; Camerer, 2003; Myerson, 1991).

Moving clockwise to the final vertex in our figure, in signaling domains, signals are often not detectable until noise is injected into a system. KSS make the point that noise can displace a true signal, but when a signal is hitherto invisible, noise can come to our rescue. This use of noise is called stochastic resonance (Harmer et al., 2002), using distributions of noise to move regular signals above the threshold where it might then be processed. A broad range of related principles include stochastic focusing (Paulsson et al., 2000) and stochastic amplification (Krakauer and Sasaki, 2002) achieves a similar goal of revealing concealed signals in collectives by adding essential variability. When signals are sparse, it becomes possible to almost perfectly re-construct a putative under-determined system using compressed sensing (Donoho, 2006). A key element of compressed sensing is the use of noisy or random sampling and random wave-forms to more effectively make measurements (Unser and Tafti, n.d).

We are not sure if you remember the story of Ludwig Boltzmann’s 1905 trip to the United States. From this trip, he wrote his celebrated essay, Journey of a German Professor to Eldorado. In the essay, he introduces an informal idea of noise that strongly resonates with yours, “My memory for numbers, usually quite reliable, always has difficulty keeping a record of glasses of beer” (Boltzmann, 1991). There are few ideas more challenging than formalizing the idea of noise and randomness. With or without a beer. But perhaps the most famous common sense idea can be found inscribed on Boltzmann’s melancholic tomb (Villani, n.d) whose epitaph is the definition of entropy

\[ S = k \log W \]

The variable \( W \) is the number of micro-states of a system and the key ingredient is the collection of particles that can adopt different configurations in a prescribed state space.

In the 1960s, Solomonoff, Kolmogorov, and Chaitin extended this idea using new ideas of algorithmic complexity (Partovi, 2001), in which randomness is defined in terms of degrees of compressibility: a perfectly random string is one for which a computer program needs to be at least as long as the string. And the length of the program is lower bounded by the entropy of the string. Through the work of Boltzmann, Kolmogorov, and others, we now know that randomness is not only essential to function in many body systems, but that it provides the foundation for the rigorous analysis of complex systems more generally.

As we see it, these relatively recent breakthroughs demonstrate that you are part of a profound tradition of bringing the subject of noise to the foreground of our thinking. We are all asking how best to model and manage variability in complex systems. And we probably all agree that when it comes to problems of collective dynamics, attending to the theory of noise is a necessary bias!

Yours,
David and David.

Response

The Costs of One Kind of Noise

Daniel Kahneman, Olivier Sibony, and Cass Sunstein

We have read your letter with great interest.

In Noise: A Flaw in Human Judgment, we defined noise as unwanted variability in human judgment. Our principal interest is in system noise, which is mostly a product of differences between judges who are expected to produce near-identical judgments (we break down these differences into two types of noise, which we call level noise and pattern noise). Occasion noise, the within-person variability of judgments, also contributes to system noise, though it is less important. Because noise is unwanted variability, it is always unwanted (by definition). At the same time, the benefits of removing or reducing it might not be worth the costs.

This statement is incorrect: “Your primary point is that if the decisions and or predictions are made by a single person, at a single moment, then noise can be (highly) deleterious.” Our primary point is certainly not that. We have a chapter on the noise of groups, in which we point out that there is unwanted variability between judgments made by groups. Our primary point is this: Wherever there is judgment, there is noise, and more of it than people think. As we define noise, it is necessarily deleterious (“unwanted variability”). A noise audit would be necessary to see how deleterious, by revealing the magnitude of noise.

You say that “noise is an essential functional requirement” in what you label “the domain of collective exploration.” You also write, “in large populations of cells classified into tissues, such as heart muscle, noise is essential in maintaining adaptability. The loss of noise in cardiac rhythms leads to a fatal determinism associated with congestive heart failure.” Our book does not argue for
congestive heart failure. (We oppose congestive heart failure.)

More seriously, it is important to emphasize that the word “noise” is wildly polysemous. We used it in the conventional sense of measurement noise, where we treated judgment as a special case of measurement. The same word is used in many other senses, to which our work relates not at all (including the common sense of “unpleasant sound” that Schopenhauer was writing about in the passage you quote). We see little purpose in discussing a heterogeneous list of situations in which something called “noise” may be recognized, sometimes with beneficial effects, if what is meant by the term is in fact entirely different in each case.

Yours,
Danny, Olivier and Cass

Response #2

The Noise of Science

David C. Krakauer and David Wolpert

As you say noise is truly polysemous. Our primary point is that in many of its various manifestations noise is extremely valuable, to be welcomed rather than avoided. Indeed, we cannot help but notice that the term ‘polysemy’ itself illustrates this benefit of noise. ‘Polysemy’ means uncertainty in the meaning of a word – i.e., noise in a word’s meaning – and this specific kind of noise is crucial for human language to be information-theoretically efficient. As a practical matter, without this kind of noise it would be impossible for humans to communicate, impossible for them to write letters to one another like the ones you and we are creating in this correspondence.

More generally, noise is a foundational principle of complex systems. Our primary focus has been to demonstrate this fact as a complement to your description of noise as deleterious. We suspect that our greatest bone of contention is the idea that eliminating “unwarranted variability” while leaving all the good stuff – the stuff that largely goes unmentioned in the book - is a perilous conceit. It is worth mentioning in this regard a similar early attitude to microbial life. In 1858 Walt Whitman writing under an assumed identity - Mose Velsor - penned a paper, “Manly Health and Training”. In his paper, which was an effort to audit the American diet, Whitman advocated for a completely vegetable free and exclusively meat-based dinner table, including the personal utility of a long beard as a sanitary protection for the throat. The idea of sanitation and purity were great nineteenth century obsessions, and the growing awareness of the microbial world, in particular in relation to contagious disease, generated a vast outpouring of interest in methods of microbial hygiene (Tomes, 1999). The importance of this understanding was no less than a revolution in healthcare.

In more recent years, largely as a result of new techniques and tools of genetics and cell biology, the idea of the “microbiome” has emerged and as a result the “ancient regime, in which our endogenous microbes were thought to be of only marginal importance, began to tumble” (Blaser, 2014). What were formerly thought of as parasitical and hazardous are now understood in equal measure as mutu-alistic and healthy. The loss of microbial variability, the loss of noise in the types of organisms that inhabit us, is the root cause of a staggering number of ailments and diseases. (Bresalier and Chapkin, 2020).

Perhaps more fundamentally, the “something called noise” is in fact the same thing not a list of unrelated situations. This gets to the heart of the criticism. In some instances, including several that you focus on, sources of randomness lead to negative consequences. But in others, far more numerous, noise is requisitioned for entirely positive objectives. The complexity of the situation is such that we cannot know which noisy consequence we are dealing with. The resolution is not to focus on eliminating the noise but modulating the mechanisms that input noisy signals to generate more or less reliable outputs.

Yours, David & David.

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References

Ackley DH, Hinton GE and Sejnowski TJ (1985) A learning algorithm for Boltzmann machines*. Cognitive Science 9(1): 147–169.

Altenberg L and Feldman MW (1987) Selection, generalized transmission and the evolution of modifier genes. I. The reduction principle. Genetics 117(3): 559–572.

Arthur S, Norman J, Welchman A, et al. (2021) The World as Will and Representation Volume 1. Schopen-Hauer: The World as Will and Representation, Cambridge, UK: Cambridge University Press, 1–4.
Binmore K and Samuelson L (1997) Muddling through: Noisy equilibrium selection. *Journal of Economic Theory* 74(2): 235–265.

Blaser MJ (2014) The microbiome revolution. *The Journal of Clinical Investigation* 124(10): 4162–4165.

Boltzmann L (1991) Journey of a German professor to Eldorado. *Transport Theory and Statistical Physics* 20(5–6):499–523.

Bresalier RS. and Chapkin RS (2020) Human microbiome in health and disease: The good, the bad, and the bugly. *Digestive Diseases and Sciences* 65(3): 671–673.

Camerer CF (2003) *Behavioral Game Theory: Experiments in Strategic Interaction*, Princeton, NJ: Princeton University Press.

Charlesworth B (1990) Optimization models, quantitative genetics, and mutation. *Evolution* 44(3): 520.

Donoho DL (2006) Compressed sensing. *IEEE Transactions on Information Theory* 52(4): 1289–1306.

Doyle JC, Francis BA and Tannenbaum AR (2013) *Feedback Control Theory*. Courier Corporation.

Fornés JA (2021) Brownian ratchets and molecular motors. *Springer Series in Biophysics* 1–14.

Goldberger AL, Amaral LAN, Hausdorff JM, et al. (2002) Fractal dynamics in physiology: Alterations with disease and aging. *Proceedings of the National Academy of Sciences* 99(Suppl 1): 2466–2472.

Harmer GP, Davis BR and Abbott D (2002) A review of stochastic resonance: circuits and measurement. *IEEE Transactions on Instrumentation and Measurement* 51(2): 299–309.

Hopfield JJ (n.d.) Neural networks and physical systems with emergent collective computational abilities. *Feynman and Computation* 7–19.

James W (n.d.) *The Dilemma of Determinism*. In: The Will to Believe and Other Essays in Popular Philosophy, pp. 145–183, 1896. Longmans Green and Co. New York

Jaynes ET (1982) On the rationale of maximum-entropy methods. *Proceedings of the IEEE* 70(9): 939–952.

Klavins E, Burden S and Napp N (2006) Optimal rules for programmed stochastic self-assembly. *Robotics: Science and Systems II*.

Kraakuer DC and Sasaki A (2002) Noisy clues to the origin of life. *Proceedings of the Royal Society of London. Series B: Biological Sciences* 269(1508): 2423–2428.

Mitchell M (1998) *An Introduction to Genetic Algorithms*. MA: Harvard University Press.

Partovi MH. Algorithmic complexity and randomness. In: AIP Conference Proceedings, 2001.

Paulsson J, Berg OG and Ehrenberg M (2000) Stochastic focusing: Fluctuation-enhanced sensitivity of intracellular regulation. *Proceedings of the National Academy of Sciences* 97(13): 7148–7153.

Rao SS (2019) *Engineering Optimization: Theory and Practice*, Hoboken, New York: John Wiley and Sons inc. 2009

Ryan TP and Morgan JP (2007) Modern experimental design. *Journal of Statistical Theory and Practice* 1(3–4): 501–506.

Settles B (2012) Synthesis lectures on artificial intelligence and machine learning. *Active learning* 6(1): 1–114.

Shimizu TS and Bray D (2021) Modelling the bacterial chemotaxis receptor complex. *Novartis Foundation Symposia* 162–181.

Smith E, Krishnamurthy S, Fontana W, et al. (2011) Nonequilibrium phase transitions in biomolecular signal transduction. *Physical Review E*, 84(5).

Steane AM (2004) Space, time, parallelism and noise requirements for reliable quantum computing. *Quantum Computing* 137–151.

Sutton RS and Barto AG (2018) *Reinforcement Learning: An Introduction*, Cambirdge MA: MIT press.

Tomes N (1999) *The Gospel of Germs*. London, England: Harvard University Press.

Unser M and Tafti PD. Sparse stochastic processes. *An Introduction to Sparse Stochastic Processes* 150–190.

van Laarhoven PJM and Aarts EHL (1987) Simulated annealing. *Simulated Annealing: Theory and Applications* 7–15.

Villani C (n.d.) H-theorem and beyond: Boltzmann’s entropy in today’s mathematics. *Boltzmann’s Legacy* 129–143.