Significance of neural noise

Gašper Štukelj

Graduate School of Systemic Neurosciences
Munich Center for Mathematical Philosophy

March 17, 2024

Graduate School of
Systemic Neurosciences
LMU Munich

What then is ~~time~~ noise? If no one asks me, I know; if I want to explain it to a questioner, I do not know.”

– ~~Augustine of Hippo~~ Gašper

What is neural noise?

What is neural noise?

Graduate School of Systemic Neurosciences
LMU Munich

- Non-deterministic source of variability in a signal. (Faisal et al., 2008)

What is neural noise?

Graduate School of Systemic Neurosciences
LMU Munich

- Non-deterministic source of variability in a signal. (Faisal et al., 2008)
- Variability of a measurement due to random or unpredictable fluctuations in the measured quantity. (McDonnell and Ward, 2011)

What is neural noise?

Graduate School of Systemic Neurosciences
LMU Munich

- Non-deterministic source of variability in a signal. (Faisal et al., 2008)
- Variability of a measurement due to random or unpredictable fluctuations in the measured quantity. (McDonnell and Ward, 2011)
- Why should philosophers care about this?

Overview

1. Fast and frugal heuristics (FFH)
2. Brains as analog computers?
3. Neuromorphic electronics – brain analogs
4. Conclusions

Overview

What are FFH?

Graduate School of Systemic Neurosciences
LMU Munich

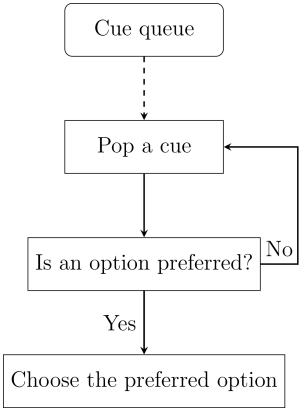
- “Simple” decision rules evolved by “biologically constrained organisms [that] function under the uncertainty of the natural world.” (Todd and Brighton, 2015).

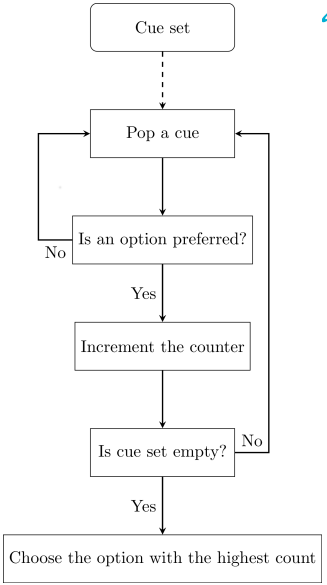
What are FFH?

Graduate School of Systemic Neurosciences
LMU Munich

- “Simple” decision rules evolved by “biologically constrained organisms [that] function under the uncertainty of the natural world.” (Todd and Brighton, 2015).
- By foregoing computation (i.e. ignoring information) decision is purportedly reached faster and under less cognitive load.

TTB (left) & Tallying (right)





Empirical inadequacy of FFH

Graduate School of Systemic Neurosciences
LMU Munich

- Overemphasis of executive functions.

Empirical inadequacy of FFH

- Overemphasis of executive functions.
- Contextual effects observed in decision-making.

Empirical inadequacy of FFH

Graduate School of Systemic Neurosciences
LMU Munich

- Overemphasis of executive functions.
- Contextual effects observed in decision-making.
- Ignoring information is cognitively tasking (Glöckner et al., 2014; Söllner et al., 2014).

“Good Ol’ Fashioned AI” legacy

Graduate School of Systemic Neurosciences
LMU Munich

- Conflation of information search & information processing.

“Good Ol’ Fashioned AI” legacy

- Conflation of information search & information processing.
- Humans as “physical symbol systems”. (Simon and Newell, 1971)

“Good Ol’ Fashioned AI” legacy

Graduate School of Systemic Neurosciences
LMU Munich

- Conflation of information search & information processing.
- Humans as “physical symbol systems”. (Simon and Newell, 1971)
- Brains as digital computers: memory bound & sequential computation.

“Good Ol’ Fashioned AI” legacy

Graduate School of Systemic Neurosciences
LMU Munich

- Conflation of information search & information processing.
- Humans as “physical symbol systems”. (Simon and Newell, 1971)
- Brains as digital computers: memory bound & sequential computation.
- Perception & motor-control imply nearly-optimal highly complex computations.

Perceptual decision-making & motor control

Graduate School of Systemic Neurosciences
LMU Munich

- Perception as categorizing noisy stimuli.

Perceptual decision-making & motor control

Graduate School of Systemic Neurosciences
LMU Munich

- Perception as categorizing noisy stimuli.
- Motor-control as a choice of a movement trajectory.

Perceptual decision-making & motor control

Graduate School of Systemic Neurosciences
LMU Munich

- Perception as categorizing noisy stimuli.
- Motor-control as a choice of a movement trajectory.
- Environmental noise as *a similar* source of risk.

Perceptual decision-making & motor control

Graduate School of Systemic Neurosciences
LMU Munich

- Perception as categorizing noisy stimuli.
- Motor-control as a choice of a movement trajectory.
- Environmental noise as *a similar* source of risk.
- Neural noise as *the common* source of uncertainty.

Dealing with uncertainty

- Ubiquitous log odds (Zhang and Maloney, 2012) & shared neural substrates (Wu et al., 2011) for representations of probabilities.

Dealing with uncertainty

Graduate School of Systemic Neurosciences
LMU Munich

- Ubiquitous log odds (Zhang and Maloney, 2012) & shared neural substrates (Wu et al., 2011) for representations of probabilities.
- Normalization as a shared neural computation underlying decision-making & explaining cross-behavioral contextual effects (Louie et al., 2013).

Perceptual decision-making & motor control

Graduate School of Systemic Neurosciences
LMU Munich

- Perception as categorizing noisy stimuli.
- Motor-control as a choice of a movement trajectory.
- Environmental noise as *a similar* source of risk.
- Neural noise as *the common* source of uncertainty.

Perceptual decision-making & motor control

Graduate School of Systemic Neurosciences
LMU Munich

- Perception as categorizing noisy stimuli.
- Motor-control as a choice of a movement trajectory.
- Environmental noise as *a similar* source of risk.
- Neural noise as *the common* source of uncertainty.
- Biological constraints?

Perceptual decision-making & motor control

Graduate School of Systemic Neurosciences
LMU Munich

- Perception as categorizing noisy stimuli.
- Motor-control as a choice of a movement trajectory.
- Environmental noise as *a similar* source of risk.
- Neural noise as *the common* source of uncertainty.
- Biological constraints? Ask a decision neuroscientist!

Neuromorphic computing

Graduate School of Systemic Neurosciences
LMU Munich

- Massive parallelism, high recurrency & mutual inhibition as main computational “motifs” (Jocham et al., 2012; Hämmerer et al., 2016).

Neuromorphic computing

Graduate School of Systemic Neurosciences
LMU Munich

- Massive parallelism, high recurrency & mutual inhibition as main computational “motifs” (Jocham et al., 2012; Hämmerer et al., 2016).
- No strong separation between memory and processing units. (Hunt and Hayden, 2017)

Neuromorphic computing

Graduate School of Systemic Neurosciences
LMU Munich

- Massive parallelism, high recurrency & mutual inhibition as main computational “motifs” (Jocham et al., 2012; Hämmerer et al., 2016).
- No strong separation between memory and processing units. (Hunt and Hayden, 2017)
- Metabolic efficiency & noise mitigation before “economic rationality”.

Upshots

- Theory of “naturalized rationality” should be aligned with the current best neuroscientific theories.

Upshots

- Theory of “naturalized rationality” should be aligned with the current best neuroscientific theories.
- Neural noise as *the common* source of uncertainty in cognitive, perceptual, and motor decision-making.

Upshots

- Theory of “naturalized rationality” should be aligned with the current best neuroscientific theories.
- Neural noise as *the common* source of uncertainty in cognitive, perceptual, and motor decision-making.
- Brains are not well-described as similar to *a* digital computer.

Upshots

Graduate School of Systemic Neurosciences
LMU Munich

- Theory of “naturalized rationality” should be aligned with the current best neuroscientific theories.
- Neural noise as *the common* source of uncertainty in cognitive, perceptual, and motor decision-making.
- Brains are not well-described as similar to *a* digital computer.
- Neuromorphic electronics as a better model of brains (Štukelj, 2019).

Overview

Maley (2018)

1. Analog computation is manipulation of analog representations.
2. Analog representations can be continuous or discrete.
3. Digital representations are discrete.
4. Brains compute with continuous signals.

$\therefore$ Brains are analog computers.

Continuous computation w/ discrete computers

- "Practically" continuous at the circuit level.
- Symbolic algebra (e.g. *exact* computation of $\sin(\pi/4)$).
- Real algebraic numbers and many transcendental numbers are Turing-computable.

Maley (2018)

- “[T]here is no discrete ‘clock’ that determines when a physical change in a circuit element should count as a change in signal.”

Maley (2018)

- “[T]here is no discrete ‘clock’ that determines when a physical change in a circuit element should count as a change in signal.”
- Temporal and rate neural codes use continuous variables.

Maley (2018)

- “[T]here is no discrete ‘clock’ that determines when a physical change in a circuit element should count as a change in signal.”
- Temporal and rate neural codes use continuous variables.
- Membrane voltage waveforms vary continuously.

Precise or “precise”?

- Neural clocks & async digital computers.

Precise or “precise”?

Graduate School of Systemic Neurosciences
LMU Munich

- Neural clocks & async digital computers.
- Falling for sloppy neuroscientific lingo?

Precise or “precise”?

Graduate School of Systemic Neurosciences
LMU Munich

- Neural clocks & async digital computers.
- Falling for sloppy neuroscientific lingo?
- Strong assumptions about the “nature of things”.

Precise or “precise”?

Graduate School of Systemic Neurosciences
LMU Munich

- Neural clocks & async digital computers.
- Falling for sloppy neuroscientific lingo?
- Strong assumptions about the “nature of things”.
- Dilution of “computationally relevant”.

Accommodating current best neurosci theories

- Presence of neural noise implies discrete computation (Eliasmith, 2000).

Accommodating current best neurosci theories

- Presence of neural noise implies discrete computation (Eliasmith, 2000).
- Adding noise to a signal does not necessarily result in a different computation.

Accommodating current best neurosci theories

Graduate School of Systemic Neurosciences
LMU Munich

- Presence of neural noise implies discrete computation (Eliasmith, 2000).
- Adding noise to a signal does not necessarily result in a different computation.
- Adding noise to a signal can result in a miscomputation – *the same* computation performed with different outcomes.

Upshots

Graduate School of Systemic Neurosciences
LMU Munich

- Noise as an indicator of discrete neural computation.

Upshots

Graduate School of Systemic Neurosciences
LMU Munich

- Noise as an indicator of discrete neural computation.
- Noise as an explanandum of neural miscomputation.

Upshots

Graduate School of Systemic Neurosciences
LMU Munich

- Noise as an indicator of discrete neural computation.
- Noise as an explanandum of neural miscomputation.
- Computational identity is closed under noise.

Overview

Douglas et al. (1995, p. 255)

Graduate School of Systemic Neurosciences
LMU Munich

The significance of neuromorphic systems is that they offer a method of exploring neural computation in a medium whose physical behavior is analogous to that of biological nervous systems.

Analog as analogous

- “Analogy machines” (von Neumann, 1951)
- Representational isomorphism (Shagrir, 2010)
- Model-based computing (Beebe, 2018)

Using physical analogs

If physical system $\mathcal{P}$ can be described as computing a function f, and $\mathcal{A}$ is its analog, then I might use $\mathcal{A}$ to:

(A1) learn about a general class of “computing strategies” for a given class of problems

Using physical analogs

If physical system $\mathcal{P}$ can be described as computing a function f, and $\mathcal{A}$ is its analog, then I might use $\mathcal{A}$ to:

(A1) learn about a general class of "computing strategies" for a given class of problems

(A2) identify particular mechanisms of $\mathcal{P}$ responsible for "implementing" f

Using physical analogs

Graduate School of Systemic Neurosciences
LMU Munich

If physical system $\mathcal{P}$ can be described as computing a function *f*, and $\mathcal{A}$ is its analog, then I might use $\mathcal{A}$ to:

(A1) learn about a general class of "computing strategies" for a given class of problems

(A2) identify particular mechanisms of $\mathcal{P}$ responsible for "implementing" f

(A3) gather *data* about $\mathcal{A}$ that can be used to reason about a hypothesis regarding $\mathcal{P}$

Douglas et al. (1995, p. 258)

Graduate School of Systemic Neurosciences
LMU Munich

The efficiency of neuromorphic analogue VLSI (aVLSI) rests in the power of analogy, the isomorphism between physical processes occurring in different media.

Using physical analogs

If physical system $\mathcal{P}$ can be described as computing a function f, and $\mathcal{A}$ is its analog, then I might use $\mathcal{A}$ to:

(A1) learn about a general class of "computing strategies" for a given class of problems

(A2) identify particular mechanisms of $\mathcal{P}$ responsible for "implementing" f

(A3) gather *data* about $\mathcal{A}$ that can be used to reason about a hypothesis regarding $\mathcal{P}$

Using physical analogs

Graduate School of Systemic Neurosciences
LMU Munich

If physical system $\mathcal{P}$ can be described as computing a function f, and $\mathcal{A}$ is its analog, then I might use $\mathcal{A}$ to:

(A1) learn about a general class of "computing strategies" for a given class of problems

(A2) identify particular mechanisms of $\mathcal{P}$ responsible for "implementing" f

(A3) gather *data* about $\mathcal{A}$ that can be used to reason about a hypothesis regarding $\mathcal{P}$

(A4) use $\mathcal{A}$ to implement f^* "efficiently"

Computing with analogs

Graduate School of Systemic Neurosciences
LMU Munich

- Isomorphism between “physical processes” not functions describing I/O.

Computing with analogs

- Isomorphism between “physical processes” not functions describing I/O.
- No distinction between target of analogy and target of computation/explanation.

I/O modeling

Graduate School of Systemic Neurosciences
LMU Munich

IN_1	IN_2	OUT
HIGH	HIGH	HIGH
HIGH	LOW	LOW
LOW	HIGH	LOW
LOW	LOW	LOW

Figure: AND or OR gate?

I/O modeling

Graduate School of Systemic Neurosciences
LMU Munich

IN_1	IN_2	OUT
HIGH	HIGH	HIGH
HIGH	LOW	LOW
LOW	HIGH	LOW
LOW	LOW	LOW

Figure: AND gate!

I/O modeling

Graduate School of Systemic Neurosciences
LMU Munich

IN_1	IN_2	OUT
HIGH	HIGH	HIGH
HIGH	LOW	LOW
LOW	HIGH	LOW
LOW	LOW	LOW

Figure: OR gate!

Using neuromorphic electronics

- Energy efficiency (Mead, 1990)

Using neuromorphic electronics

- Energy efficiency (Mead, 1990)
- Parallelism (Schuman et al., 2017)

Using neuromorphic electronics

- Energy efficiency (Mead, 1990)
- Parallelism (Schuman et al., 2017)
- Synchronization of isolated circuits w/ noise (Utagawa et al., 2008)

Using neuromorphic electronics

Graduate School of Systemic Neurosciences
LMU Munich

- Energy efficiency (Mead, 1990)
- Parallelism (Schuman et al., 2017)
- Synchronization of isolated circuits w/ noise (Utagawa et al., 2008)
- Stochastic resonance (Gonzalez-Carabarin et al., 2014)

McDonnell and Ward (2011, p. 417)

Graduate School of Systemic Neurosciences
LMU Munich

> *[S]tochastic resonance is often described as paradoxical or counter-intuitive, because in engineered electronic systems noise is naturally seen to be only detrimental to quality. However, in a biological context, the effect is hardly counter-intuitive when thought of as the benefits of randomness, as with other constructive roles of noise in which inputs and outputs need not be readily identifiable.*

McDonnell and Ward (2011, p. 417)

Graduate School of Systemic Neurosciences
LMU Munich

[S]tochastic resonance is often described as paradoxical or counter-intuitive, because in engineered electronic systems noise is naturally seen to be only detrimental to quality. However, in a biological context, the effect is hardly counter-intuitive when thought of as ***the benefits of randomness****, as with other* ***constructive roles of noise in which inputs and outputs need not be readily identifiable.***

Upshots

Graduate School of Systemic Neurosciences
LMU Munich

- Analogies/isomorphisms go over and above I/O relationships.

Upshots

Graduate School of Systemic Neurosciences
LMU Munich

- Analogies/isomorphisms go over and above I/O relationships.
- Some computations are driven by non-computational goals.

Overview

Conclusions

- Recognition of noise as a cross-behavioral source of uncertainty has driven the unification of decision neuroscience.

Conclusions

- Recognition of noise as a cross-behavioral source of uncertainty has driven the unification of decision neuroscience.
- The concept of noise plays an important role in neuroscientific explanations & related philosophical arguments.

Conclusions

- Recognition of noise as a cross-behavioral source of uncertainty has driven the unification of decision neuroscience.
- The concept of noise plays an important role in neuroscientific explanations & related philosophical arguments.
- Neuromorphic computers are analog computers by virtue of physical behavior analogous to brains.

Thank you!

TAC

Stephan Hartmann
Stefan Glasauer
Ophelia Deroy
Gregory Wheeler

Universität Bern

Andrea Loettgers

Neurophilosophy group

Stephan Sellmaier
Sachith Cheruvatur

MCMP

Cameron Beebe
Joe Dewhurst
Timo Freiesleben

Klinikum Rechts der Isar

Mónica Emch

Family & Friends

GSN & DFG

References

Beebe, C. (2018). Model-based computation. *Natural Computing*, 17(2):271–281.

Eliasmith, C. (2000). Is the brain analog or digital? *Cognitive Science Quarterly*, 1(2):147–170.

Faisal, A., Selen, L., and Wolpert, D. (2008). Noise in the nervous system. *Nature reviews. Neuroscience*, 9:292–303.

Glöckner, A., Hilbig, B. E., and Jekel, M. (2014). What is adaptive about adaptive decision making? a parallel constraint satisfaction account. *Cognition*, 133(3):641–666.

Gonzalez-Carabarin, L., Asai, T., and Motomura, M. (2014). Application of nonlinear systems for designing low-power logic gates based on stochastic resonance. *Nonlinear Theory and Its Applications, IEICE*, 5(4):445–455.

References

Hämmerer, D., Bonaiuto, J., Klein-Flügge, M., Bikson, M., and Bestmann, S. (2016). Selective alteration of human value decisions with medial frontal tDCS is predicted by changes in attractor dynamics. *Scientific Reports*, 6(1):25160.

Hunt, L. T. and Hayden, B. Y. (2017). A distributed, hierarchical and recurrent framework for reward-based choice. *Nature Reviews Neuroscience*, 18(3):172–182.

Jocham, G., Hunt, L. T., Near, J., and Behrens, T. E. J. (2012). A mechanism for value-guided choice based on the excitation-inhibition balance in prefrontal cortex. *Nature Neuroscience*, 15(7):960–961.

Louie, K., Khaw, M. W., and Glimcher, P. W. (2013). Normalization is a general neural mechanism for context-dependent decision making. *Proceedings of the National Academy of Sciences*, 110(15):6139–6144.

References

Maley, C. (2018). Toward analog neural computation. *Minds and Machines*, 28(1):77–91.

McDonnell, M. and Ward, L. (2011). The benefits of noise in neural systems: Bridging theory and experiment. *Nature Reviews Neuroscience*, 12:415–425.

Mead, C. (1990). Mead c (1990, october) neuromorphic electronic systems. proc ieee. *Proceedings of the IEEE*, 78:1629 – 1636.

Schuman, C. D., Potok, T. E., Patton, R. M., Birdwell, J. D., Dean, M. E., Rose, G. S., and Plank, J. S. (2017). A survey of neuromorphic computing and neural networks in hardware. *ArXiv*, abs/1705.06963.

Shagrir, O. (2010). Brains as analog-model computers. *Studies in History and Philosophy of Science Part A*, 41(3):271–279.

References

Simon, H. A. and Newell, A. (1971). Human problem solving: The state of the theory in 1970. *American Psychologist*, 26(2):145–159.

Söllner, A., Bröder, A., Glöckner, A., and Betsch, T. (2014). Single-process versus multiple-strategy models of decision making: Evidence from an information intrusion paradigm. *Acta Psychologica*, 146:84–96.

Todd, M., P. and Brighton, H. (2015). Building the theory of ecological rationality. *Minds and Machines*, 26(1-2):9–30.

Utagawa, A., Asai, T., Hirose, T., and Amemiya, Y. (2008). Noise-induced synchronization among sub-rf cmos analog oscillators for skew-free clock distribution. *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, E91.A(9):2475–2481.

References

von Neumann, J. (1951). The general an logical theory of automata. *Cerebral mechanisms in behavior*, 5:1–41.

Štukelj, G. (2019). On the simplicity of simple heuristics. *Adaptive Behavior*. https://doi.org/10.1177/1059712319861589.

Wu, S.-W., Delgado, M. R., and Maloney, L. T. (2011). The neural correlates of subjective utility of monetary outcome and probability weight in economic and in motor decision under risk. *Journal of Neuroscience*, 31(24):8822–8831.

Zhang, H. and Maloney, L. T. (2012). Ubiquitous log odds: A common representation of probability and frequency distortion in perception, action, and cognition. *Frontiers in Neuroscience*, 6:1.