

# VU Research Portal

## Reply to Muscoloni and Cannistraci: Navigation performance measures

Seguin, Caio; Van Den Heuvel, Martijn P.; Zalesky, Andrew

### **published in**

Proceedings of the National Academy of Sciences of the United States of America  
2019

### **DOI (link to publisher)**

[10.1073/pnas.1820315116](https://doi.org/10.1073/pnas.1820315116)

### **document version**

Publisher's PDF, also known as Version of record

### **document license**

Article 25fa Dutch Copyright Act

[Link to publication in VU Research Portal](#)

### **citation for published version (APA)**

Seguin, C., Van Den Heuvel, M. P., & Zalesky, A. (2019). Reply to Muscoloni and Cannistraci: Navigation performance measures. *Proceedings of the National Academy of Sciences of the United States of America*, 116(5), 1470-1470. <https://doi.org/10.1073/pnas.1820315116>

### **General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

### **Take down policy**

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

### **E-mail address:**

[vuresearchportal.ub@vu.nl](mailto:vuresearchportal.ub@vu.nl)

## REPLY TO MUSCOLONI AND CANNISTRACI:

# Navigation performance measures

Caio Seguin<sup>a,1</sup>, Martijn P. van den Heuvel<sup>b,c</sup>, and Andrew Zalesky<sup>a,d</sup>

Muscoloni and Cannistraci (1) comment on our motivation and rationale for using the efficiency ratio to assess the feasibility of navigation routing as a model of communication in nervous systems embedded in Euclidean space (2). Recent work by these authors in the field of network physics evaluates navigation in hyperbolic space using the greedy routing score (3), a measure equivalent to the efficiency ratio.

The efficiency ratio ( $E_R$ ) is the ratio of the efficiency of navigation paths ( $E$ ) to that of shortest paths ( $E^*$ ). We used the efficiency ratio to demonstrate that the topology and geometry of mammalian cortical networks allows for near-optimal decentralized communication under navigation routing. We provided a mathematical definition of the efficiency ratio in equation 1 of ref. 2. Furthermore, we provided a rationale for using the efficiency ratio and described how this measure relates to the proportion of failed/successful navigation paths, previously quantified with the success ratio (4, 5). These details can be found in the main text of Seguin et al. (ref. 2, p. 2) in *Navigation Performance Measures* and in figure 2 of ref. 2. In particular, we wrote

$E$  quantifies both the number of failed paths and the efficiency of successful paths. We defined the efficiency ratio

$$E_R = \frac{1}{N^2 - N} \sum_{i \neq j} \frac{\Lambda_{ij}^*}{\Lambda_{ij}} \quad [1]$$

to compare navigation with shortest path routing. For any network,  $E^* \geq E$  and thus  $0 \leq E_R \leq 1$ . The closer  $E_R$  is to 1, the better navigation is at finding paths that are as efficient as shortest paths.

Muscoloni and Cannistraci (1) also argue that “greedy routing” is a more appropriate terminology compared with “navigation” routing. Our choice of terminology was motivated by the common use of terms such as “navigability,” “navigation problem,” “navigation efficiency,” and “navigation games,” among others (4–6).

Our study shows that navigation routing is a feasible model of large-scale neural communication. We hope that our work will motivate further study of navigation and communication in brain networks. Recent public release of high-quality invertebrate and mammalian connectomes heralds new opportunities to study the principles underlying information transfer in nervous systems. Understanding these principles will be crucial to predicting the effects of lesions and focal brain stimulation as well as advancing knowledge of behavior and cognition (7).

- 1 Muscoloni A, Cannistraci CV (2019) Navigability evaluation of complex networks by greedy routing efficiency. *Proc Natl Acad Sci USA* 116:1468–1469.
- 2 Seguin C, van den Heuvel MP, Zalesky A (2018) Navigation of brain networks. *Proc Natl Acad Sci USA* 115:6297–6302.
- 3 Muscoloni A, Thomas JM, Ciucci S, Bianconi G, Cannistraci CV (2017) Machine learning meets complex networks via coalescent embedding in the hyperbolic space. *Nat Commun* 8:1615.
- 4 Boguna M, Krioukov D, Claffy KC (2009) Navigability of complex networks. *Nat Phys* 5:74–80.
- 5 Gulyás A, Biró JJ, Kőrösi A, Rétvári G, Krioukov D (2015) Navigable networks as Nash equilibria of navigation games. *Nat Commun* 6:7651.
- 6 Simšek O, Jensen D (2008) Navigating networks by using homophily and degree. *Proc Natl Acad Sci USA* 105:12758–12762.
- 7 Avena-Koenigsberger A, Misic B, Sporns O (2017) Communication dynamics in complex brain networks. *Nat Rev Neurosci* 19:17–33.

<sup>a</sup>Melbourne Neuropsychiatry Centre, The University of Melbourne and Melbourne Health, Melbourne, VIC 3010, Australia; <sup>b</sup>Dutch Connectome Lab, Department of Complex Trait Genetics, Center for Neurogenomics and Cognitive Research, Amsterdam Neuroscience, VU University Amsterdam, 1081 HV Amsterdam, The Netherlands; <sup>c</sup>Department of Clinical Genetics, Amsterdam Neuroscience, VU University Medical Center, 1081 HV Amsterdam, The Netherlands; and <sup>d</sup>Department of Biomedical Engineering, Melbourne School of Engineering, The University of Melbourne, Melbourne, VIC 3010, Australia

Author contributions: C.S., M.P.v.d.H., and A.Z. wrote the paper.

The authors declare no conflict of interest.

Published under the [PNAS license](#).

<sup>1</sup>To whom correspondence should be addressed. Email: caioseguin@gmail.com.

Published online January 10, 2019.