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Information theoretic bounds on the effectiveness of neural prosthetics

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Capacity defines the ultimate fidelity limits of information transmission by any system, be it conveyed by digital, analog or spike train signals. Rate-distortion theory shows that regardless of how error is defined, any system having a smaller capacity than another must result in larger estimation errors. For example, this theory shows that, for bandlimited Gaussian stimuli, the smallest possible mean-squared error decays exponentially with capacity. Since a single neuron's capacity is proportional to peak spike rate, $\varepsilon^2_{\min} \propto \exp\{-\lambda_{\max}/eW\}$ (W is the stimulus bandwidth).

In previous work, we derived the capacity of parallel Poisson process channels, which allows us to study the relative effectiveness of neural population structures. Here, we elaborate those results for two models of neural prosthetics: (1) electrical stimulation systems such as cochlear implants and (2) neural control systems that use surface or gross potentials to control movements of limb prostheses. We show that for the electrical stimulation case, the capacity is proportional to the size of the population being stimulated, regardless of whether the stimulus drives the entire population or whether individual neurons are independently stimulated (fig 1). In this case, gross stimulation theoretically suffices. In contrast, neural control systems using gross recordings have a far smaller capacity. If a single potential represents the aggregate population activity, we found that capacity does not increase with population size, but instead saturates at a value less than the capacity provided by using the individual outputs of two neurons to derive the control signal. If two gross potential measurements are made, assumed here to represent overlapping subpopulations, capacity is larger than in the single-potential case but still saturates with increasing population size.

We conclude that stimulation prosthetics face no fundamental barriers to being effective. Neural control systems do, however. This fundamental limitation can be overcome by using spike sorting (teasing apart the gross poten-

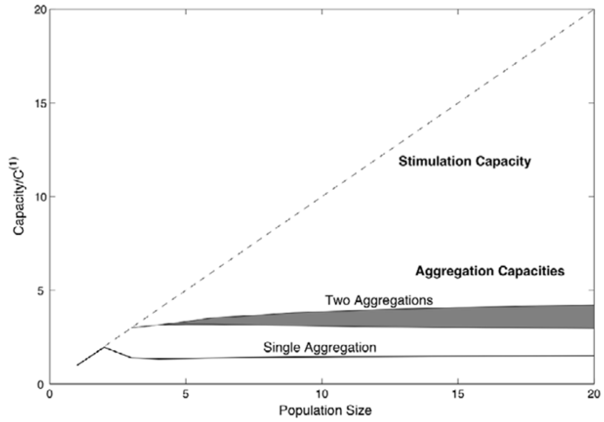

Figure 1
Capacity as a function of neural population size.

tial into its constituents) and/or by using feedback, which has been shown to increase capacity.