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# The effect of sparseness in distributed representations on the detectability of associations between sensory events

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Nervous systems are often able to establish when two sensory events are associated with each other, in the sense of occurring together more often than would be expected by chance on the basis of their separate probabilities. Sensory events do not, however, all have a specific or 'grandmother cell' representation in which there is one-to-one correspondence between occurrence of the whole pattern and firing of an individual neuron. Neurons can only perform computations on information available to them locally. With overlapping representations of sensory events, distributed across a set of neurons, detection of an association can therefore at best be a process of pooling noisy information (corrupted through overlap) about associations involving the separate cells active in an event. The extent to which this degrades detectability of associations can be measured by Fisher's concept of 'statistical efficiency', i.e. the reciprocal of the factor by which the number of observations required to reject the null hypothesis of statistical independence is increased.

We have examined, using statistical theory, the effects of the proportion ($\alpha$) of cells active in the representation of an event $X$ on the statistical efficiency for detection of associations with a separate event $R$ ('reinforcement') assumed to have a specific representation. If $\alpha$ is the same for all events, $X$ and not-$X$, then efficiency rises as $\alpha$ falls. For example, if it takes 100 bits to define $X$, the information can in principle be reversibly recoded as 50 active cells out of 100 ($\alpha = 0.5$) down to 1 active cell out of $10^{30}$ ($\alpha = 10^{-30}$). The theoretically attainable statistical efficiency in a typical situation rises from $< 1$ % at $\alpha = 0.5$ to 20 % at $\alpha = 0.1$, 65 % at $\alpha = 0.01$, and almost 100 % at $\alpha = 0.001$ (Conditions: $P(X) = 0.001$, $P(R|X) = 0.75$, $P(R|\text{not-}X) = 0.25$; identical overall probabilities of firing at all cells). The advantage of recoding events to a lower activity ratio is achieved at the cost of the use of a larger cell population, in this case rising from $10^2$ to $10^4$ for maximal advantage. Such seemingly extravagant recoding is known to occur in sensory systems.

With a given average activity ratio $\alpha$ over all events, it is possible to vary $\alpha_X$ for one event $X$. The greater $\alpha_X$, the greater is the statistical efficiency for $X$, at the expense of the efficiency for other events. Events with low relative frequency require a higher $\alpha$ for the same efficiency. Thus $\alpha_X$ reflects a form of competitive signal strength for $X$. With a range of events having different frequencies, the optimal coding for uniform statistical efficiency assigns above average activity ratios to rare events and below average ratios to more common events.