Cognitive Neuroscience

Dynamic Core Theory and Neural Darwinism

December 2, 2008

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Explaining consciousness has become a key area of research and debate in the world of neuroscience. The underlying concept behind Gerald Edelman's Dynamic Core Theory on consciousness is based on a dynamic cluster of neuronal groups in the thalamocortical region that interact with each other across various areas in the brain (Tononi & Edelman, 1998). This theory is linked with Edelman's theory of neural Darwinism, which emphasizes the selectionist nature of brain development rather than the instructionist computer analogy of the brain (Edelman, 2004). While it is difficult to know for sure which theory of consciousness, if any, will stand the test of time, Edelman's is an important contender among explanations of consciousness. Moreover, an important contribution associated with this theory is the possibility to quantitatively measure certain aspects of consciousness, which Edelman and Tononi (1998) suggest by using certain formulas to calculate integration and differentiation of neural processes.

In order to explain the dynamic core theory, it is essential to also discuss a few major concepts. The first is the nature of consciousness, for which there have been a few basic and physiological findings. One is that the thalamocortical system is essential to conscious functions: studies show that damage to the brainstem or thalamus eliminates the state of consciousness (Seth & Baars, 2005). However, damage to the sensory cortex, only seems to abolish specific elements of the conscious experience (Seth & Baars, 2005). This brings up an important concept in Edelman's approach: rather than correlate intrinsic properties of certain neurons or specific brain areas with consciousness, he looks at global processes that take place among widespread groups of neurons (Edelman, 2003). He explains that a 'global' theory is needed because the

experience of consciousness includes perception, memory, intentions, among other elements, and does not just correspond to one isolated brain region (Edelman, 2004). Moreover, studies on sensory input that reaches consciousness demonstrate that consciousness spreads to diverse areas of the brain, while those inputs that do not register consciously only activate local areas (Seth & Baars, 2005).

 Another feature of conscious experience that is susceptible to quantitative measurement is that only one conscious scene occurs at a time (Seth, Izhikevich, Reeke & Edelman, 2006). Moreover, the speed at which conscious scenes are capable of making distinctions in perception and memory demonstrates the rapid adaptability of conscious experience (Seth et al., 2006).

Degeneracy is an important concept related to conscious experience. It is also a key feature that distinguishes the brain from computers, making instructionist or computer models less suited for explaining brain processes (Edelman, 2004). Degeneracy describes how different circuits or neural systems are capable of creating the same behavior or function – much like how various strings of codons in genetic codes can create the same amino acids (Edelman, 2004). Degeneracy in the brain is reflected by the fact that different brain structures can influence the same motor behavior: when a lesion occurs in a certain area, alternative pathways are created to perform that same motor output (Tononi, Sporns & Edelman, 1999). An example of degeneracy at the neural level, is represented in changes in expressions of genes that can be brought on by differing input combinations (Tononi et al., 1999).

The term redundancy is often conflated with degeneracy, however, even though they have different meanings (Tononi et al., 1999).   As Edelman and Gally (2001) point out,

the term "functional redundancy" occurs when the same output is performed by *identical* elements, which ignores the key feature of degeneracy, namely that *structurally different* elements result in the same output (p. 13763). Edelman and Gally (2001) also assert that redundancy is misleading because it implies that a certain property is specifically selected during evolution, while on the contrary they maintain that degeneracy "is not a property simply selected by evolution, but rather is a prerequisite for and an inescapable product of the process of natural selection itself" (p.13763). Moreover, the complexity of a neural network is reflected in a high level of degeneracy, not redundancy (Tononi et al., 1999). This complexity is due to the fact that many different elements can influence a behavior or output in a similar way while also having their own independent output, thus demonstrating functional specialization as well as functional integration (Edelman & Gally, 2001). This level of complexity increases the adaptability of neural networks to unpredictable changes because many different elements can interact in different environments and with different constraints to create the same output (Edelman & Gally, 2001).

Degeneracy is therefore a principle reason for so much variation within neuronal groups and is in fact a necessary component of natural selection (Edelman & Gally, 2001). This variation leads to another element of the dynamic core theory: Neural Darwinism (ND) (Seth & Baars, 2005). Neural Darwinism emphasizes the importance of size and variation within populations (Seth & Baars, 2005). Individual differences within each brain make up populations of variants, which means that both variation and numbers are enormous due to differing factors such as genetic influence and histories in varying environments (Edelman, 2004).

[L SEP]　From within this large and varied population of neuronal groups, evolution selects those groups that meet certain fitness or value-related criteria (Edelman, 2004). In the brain, these criteria are based on a value or rewards system that controls responses necessary for survival (Edelman, 2004). Value in this context refers to whether an event is negatively or positively salient for the organism as determined by evolution or learning (Seth et al. 2006). The synaptic populations that satisfy these criteria are more likely to survive or contribute to behavior (Edelman, 2004). Neural Darwinism is therefore also referred to as the theory of neuronal group selection (TNGS) (Edelman, 2004).

[L SEP]　Three major tenets comprise the TNGS. The first is the stage of developmental selection, which occurs early on in the development of neuroanatomy and creates repertoires of circuits based on variation in patterns of developing neurons (Edelman, 2004). As Edelman (2004) explains, "the neurons that fire together wire together during the fetal and embryonic stage" (p.37). The second tenet is the phase of experiential selection, during which the array of input from the environment leads to large variations of synaptic strengths (Edelman, 2004). Both of these phases demonstrate a high degree of degeneracy (Seth & Baars, 2005).

[L SEP]　The third tenet, reentry, is critical to the concept of Neural Darwinism and is the link between ND and the explanation of consciousness (Edelman, 2003). Reentry refers to a dynamic, two-way interchange of signals between disjunctive groups of neurons located in various brain areas (Edelman, 2004). This simultaneous and reciprocal communication of signals forms a functional circuit that allows for the coordination of brain activity across space and time (Edelman, 2004). Reentry is what

binds together various features of a visual object, such as color and movement

(Edelman, 2004). Moreover, reentrant interactions between posterior areas of the brain

linked with perceptual categorization and anterior areas responsible for memory are a

main mechanism in conscious experience (Tononi & Edelman, 1998).   Reentry permits

an animal to respond adaptively to its environment by linking value-based memories

with current perceptual categorization, (Seth & Baars, 2005).

  Edelman proposes that the link between ND, the dynamic core theory and

consciousness is found in neural activity in the thalamocortical core, a highly

interconnected and therefore ideal system for the integrative and differentiated qualities

of conscious experience (Seth & Baars, 1998).   The dynamic core theory emphasizes

integration and differentiation as key elements because each conscious experience is a

"scene" that cannot be decomposed into independent elements and involves the rapid

selection of one conscious scene over a massive number of others (Tononi & Edelman,

1998, p.1846).   A neural process leads to an integrated process and can be

quantitatively measured as such if the distributed elements within that system interact

with each other much more strongly than with the rest of the elements in the system,

such as in a functional cluster (Tononi & Edelman, 1998).   A functional cluster is a

unified neural process that is integrated, independent and cannot be further divided into

any smaller subsets (Tononi & Edelman, 1998).

  Differentiation is the other key element of the dynamic core theory. The

occurrence of a given conscious state results from the fact that it was selected among

billions of others within a fraction of a second (Tononi & Edelman, 1998). This

selection yields both an enormous amount of information because it reduces uncertainty

as well as important information, because it will have related consequences (Tononi & Edelman, 1998).   Differentiation can be measured by the degree of complexity within an integrated neural process, which is reflected by the emergence of a large array of different activity patterns within that system (Tononi & Edelman, 1998).   Neural complexity refers to the concept that small neural subsets within a system act independently but large subsets are coherent within the system, reflecting a level of dynamic integration (Seth et al., 2006). In their article, *Theories and measures of consciousness: An extended framework*, the authors provide a brief overview of the formula: "the neural complexity […] of a system X composed of n elements is equal to the sum of the average mutual information across all bipartitions of the system" (Seth et al., 2006, p. 10800).   We see then, that the level of complexity of a system is associated with the information that is shared among the various subsets.

⸛ An important element of the Dynamic Core theory is that activity of a distributed functional cluster in the thalamocortical region can only contribute to conscious experience if it is integrated rapidly, which can be achieved through reentry (Tononi & Edelman, 1998). Moreover, only functional clusters with high levels of differentiation can sustain conscious experience.⸛ This may explain why stimuli that are weak and short-lived do not reach conscious perception (Tononi & Edelman, 1998). As Tononi and Edelman (1998) explain, neural activity that is sustained for hundreds of milliseconds is more likely to contribute to distributed neural interactions, thereby leading to activity among reentrant loops across larger distances.   In fact, their measurements indicate that 500 ms of somatosensory stimuli to the thalamus are

required to invoke a conscious experience, while 150 ms is enough for perception without awareness (Tononi & Edelman, 1998).

    Although this aspect of conscious experience is quantifiable, various considerations must be made in any approach to measuring consciousness in general. One key consideration is that consciousness cannot be measured as a thing or unit (Seth et al., 2006). Consciousness involves an interplay between environment and organism and is a type of transactional process between different types of sensory inputs (Seth et al., 2006). To be useful, the measurement must also take into account the causal relationship between environment and organism (Seth et al., 2006). Moreover, if the measurement is not able to compute large numbers of neuronal elements, it may not be useful (Seth et al., 2006).

    The calculation of integration within a system is an attempt to satisfy the criteria of causal relationship because it measures "effective information" - which is the calculation of mutual information shared over a partition in the system; however, as Seth et al. (2006) demonstrate, this calculation is infeasible because it must take into account the number of bipartitions in a system (p.10801). The number of bipartitions grows in relationship to the growth of the network, but since there is not yet a way of approximating this number, the computation will not work for large networks (Seth et al., 2006).

    While it is clear to many experts in cognitive neuroscience that consciousness in its entirety may never be completely quantifiable, efforts to empirically measure certain elements of conscious experience are still valuable (Seth et al., 2006). This is partly because the ability to measure certain elements may lead to the identification of other

measurable elements. Perhaps more importantly, however, is that quantification of consciousness could provide information on non-human animal experiences of consciousness, and could also shed light on the processes of anesthesia and neurological and psychiatric disorders (Seth et al., 2006).

[SEP]   Edelman's emphasis on the elements of integration and differentiation underlying consciousness and his approach to quantitatively identify these elements has already opened up extensive avenues of research into consciousness. In terms of quantitative measurements of consciousness, the dynamic core theory has made certain aspects amenable to measurement; however, no single measure seems capable of summing up consciousness as a whole (Seth et al. 2006). Moreover, although there may be improvements and progress in the quantitative evaluation of conscious elements, there will continue to be some aspects that will defy quantification, leaving the full evaluation of conscious experience to both quantitative and qualitative measures (Seth et al., 2006). Whether the dynamic core theory will stand the test of time is unknown; however, the principles and tenets behind them and the already emerging possibility of measuring certain elements will allow future research to expand upon our understanding of consciousness beyond what most people likely ever imagined. [SEP]

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