Axon Interaction for the Novice

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Abstract

In this note, the author presents the rudiments of axon-axon interaction for the beginner, without the use of equations.

Consider a nervous system which has a brain, a spinal cord, and the spinal cord has alongside it several ganglion or ganglia in plural. These ganglia are the root of the nervous system as it spreads into the body at large. Now if we think in this nervous system there are nerves which take signals both upwards and downward meaning from the ganglia near the base of the spinal cord upward, towards the cerebral cortex and back towards these ganglia at the base of the spinal cord. When we think anatomically we immediately think of a three-dimensional mass of nerve cells which is known as gray matter and axons, their extended processes, which is known as white matter and we also zoom in a bit into certain regions of the white matter and gray matter which contain longitudinal extended processes known as axons on one end originating from the soma of cells and from the other end terminating upon the somata of other cells in what are known as synaptic connections.

Consider one of these synapses at which an axon's terminal bouton impinges as the action potential flows down the axon and reaches the terminal bouton. At the bouton cell membrane or axonal membrane charges flow in and out borne by calcium ions. These calcium ions then lead to the release of vesicles called synaptic vesicles into the synapse. These vesicles contain neurotransmitters - certain molecules - which then travel across the synaptic junction and are captured in holes and pegs into which they fit snugly and cause the opening of ion channels in the post-synaptic cell. This process of neurotransmission takes place at a synapse and leads to the hopping of the action potential train from one axon in a nerve cell to the next nerve cell.

Consider just such a bunch of axons arranged in some geometry not necessarily parallel to one another but even inclined towards one another at certain different and individual angle. Further specify the distances between these let's say four or five axons in the cross sectional plane. Obviously since the four or five axons are inclined at angles, various angles to the perpendicular drawn on the cross sectional plane, therefore depending upon where one takes the cross section one will get a unique and distinct set of distances between the axonal cross sections themselves. Call the collection of four or five axons as a tract of axons. In this way we can distinguish the collection from its members: members are axons and the collection is called a tract.

The cross section that we just talked about first was the tract cross section and then we mentioned briefly the axonal cross sections for taking the inter axonal distances. So here's the geometry of the setting. We have say four or five axons in a tract and these axons are inclined to the tract axis which is perpendicular to the cross section in which we measure the interaxonal distances for different values of the parameter along the tract axis which tells us where we have placed the tract cross section.

Given this geometry, namely the interaxonal distance matrix and the angles of inclination of the various axons to the tract axis, we then stimulate say one or two of these axons out of four or five and observe the propagation of impulses down the axis and down the tract of axons. We also look for synchronization in this geometry. Why would these axons synchronize the impulses borne on them? Why would they synchronize? If we assume that the entire tract is electrically neutral and isolated from outside - insulated I mean to say - then any current which is introduced by the axons or single axon in one direction must be compensated by a reverse current in the extracellular space. This current balance or fine current balance leads to coupling between the various axons all of which are balanced by the same extracellular current.

This mechanism of coupling reminds us of two pendula oscillating to and fro, suspended from the same horizontal bar. The common medium of the horizontal bar ensures that their oscillations cannot be independent of one another. If I place a cork, in another example, on the surface of a tank of water and perturb this water surface so that ripples arise, the cork will bob up and down. If next I place another cork at a certain distance from it, the two corks will both bob up and down perhaps in a complex relationship but in a relationship nevertheless because they are perturbed by the same underlying single water body. Thus we see that the presence of a coupling medium is essential for coupling to take place.

This is in contrast to the propagation of electromagnetic waves which doesn't require any medium whatsoever. So if I have an electric charge flowing up and down in an antenna-like structure at one point which then radiates electromagnetic waves which are received by the receiving antenna which cause the current to flow in it in a similar oscillatory pattern. There is no common medium between the transmitting and the receiving antenna yet there is a coupling wave between the transmitter and the receiver due to a field which is present. And the field can exist even in vacuum. Therefore the mechanism of coupling between a transmitting EM wave antenna and a receiving EM wave antenna is a medium-less coupling.

We may wonder if, in the absence of a medium of coupling, and replacement of the medium by a field and waves in the field, if there is a fundamental distinction between these two conditions or scenarios. Let me repeat once again: on the one hand we have two charges at different points and they are placed in vacuum. So there is no mechanical medium between them, yet when I oscillate one of them the other one also sympathetically oscillates and I compare this with two pendula, one at one point of a mechanical suspending rod and the other at the other end of it. So that when I vibrate one of them the other one oscillates in response due to the mechanical medium between the two pendula.

These two settings, when they are compared, tell us that regardless of whether there is a medium of coupling, the mode of coupling is a carrier wave. In the case of the pendulum the mechanical substrate transmits vibratory waves from one side to the other whereas in the case of the two charges even in the absence of a medium, electric field waves propagate from one charge to the other and couple the oscillation.

Thus we see that synchronization or coupled oscillation is indifferent to the presence of a medium and rather relies on waves which don't necessarily need a medium. Thus synchronization or coupling is wave-matter interaction. We will come back to this point of view a little later but for now suffice it to say that the extracellular medium bears current and the current balance causes the coupling. This coupling is known as ephaptic coupling.