Learning STEM Through Integrative Visual Representations

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ABSTRACT

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Previous cognitive models of memory have not comprehensively taken into account the internal cognitive load of chunking isolated information and have emphasized the external cognitive load of visual presentation only. Under the Virk Long Term Working Memory Multimedia Model of cognitive load, drawing from the Cowan model, students presented with integrated animations of the key neural signal transmission subcomponents where the interrelationships between subcomponents are visually and verbally explicit, were hypothesized to perform significantly better on free response and diagram labeling questions, than students presented with isolated animations of these subcomponents. This is because the internal attentional cognitive load of chunking these concepts is greatly reduced and hence the overall cognitive load is less for the integrated visuals group than the isolated group, despite the higher external load for the integrated group of having the interrelationships between subcomponents presented explicitly.

Experiment 1 demonstrated that integrating the subcomponents of the neuron significantly enhanced comprehension of the interconnections between cellular subcomponents and approached significance for enhancing comprehension of the layered molecular correlates of the cellular structures and their interconnections. Experiment 2 corrected time on task confounds from Experiment 1 and focused on the cellular subcomponents of the neuron only. Results from the free response essay subcomponent subscores did demonstrate significant differences in favor of the integrated group as well as some evidence from the diagram labeling section. Results from

free response, short answer and What-If (problem solving), and diagram labeling detailed interrelationship subscores demonstrated the integrated group did indeed learn the extra material they were presented with. This data demonstrating the integrated group learned the extra material they were presented with provides some initial support for the assertion that chunking mediated the greater gains in learning for the neural subcomponent concepts over the control.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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CHAPTER I

INTRODUCTION

Students often have a very difficult time learning STEM subjects because the causal connections between related scientific concepts are not made visually manifest for them. Instead, students are presented with isolated visual and verbal descriptions of the subcomponents (i.e., a dendrite, a sodium channel) of a complex scientific system, such as the neuron/action potential, without a strong holistic visual representation of how the various subcomponents relate to one another. Without seeing how one part of a complex scientific system, such as dendrite in the neuron, relates to another part of a complex scientific system, such as phospholipids which line the neuron in dense areas called the myelin sheath, students do not have a strong spatial understanding of the emergent properties of the complex system as a whole, the neural action potential, and subsequently also do not conceptualize the subcomponents themselves at a deeper, more spatial level.

Overall, the instructional practice of providing students with the context of the integrated whole, such as a neuron animation with all its subcomponents integrated together, helps them greatly in chunking the subparts, such as dendrites and phospholipids, and leads to a deeper, more spatial understanding of the subparts and system as a whole. The Cowan Long Term Working Memory framework is used as a foundation for the theory behind this study, as it affords a more transparent and precise model for how grades of attention are directed towards concepts being activated in a consolidated memory store called long term working memory, such as the subcomponents of a neuron and the interconnections among subcomponents, and takes into account all of the five major modalities.

Sweller (1990), would advocate that presenting external information which elaborates beyond the core neural sub-components presented to each condition would increase the overall cognitive load of retention and recall and result in worse retention of the neural components in the integrated neural animated condition versus the isolated neural animated condition. However, under our version of the Cowan model, it is predicted that while the additional visual imagery and details used to assemble subcomponents of a complex system, such as the dendrites, calcium/Na+/K+ channels of a neuron, into the integrated system, here an entire neuron, increases the external central executory modulated attentional cognitive load of the presentation (let's say 30 units of "load"), it greatly decreases the internal cognitive load of chunking these subcomponents together (5 units of "load"), leading to an overall much lower summed external + internal cognitive load for the presentation overall (here, 35 units of "load"), versus an isolated presentation. Here, the isolated presentation has a much lower external cognitive load (let's say 10 units of "load"), as the extra visual imagery used to show interconnections between subcomponents in absent, such as visualizing how a dendrite relates to a calcium channels in a neuron, but has a much greater internal cognitive load of processing and chunking the unchunked subcomponents (50 units of "load"), such as dendrites, ion channels and phospholipids, and hence a greater sum cognitive load (10+50=60 units of "load").

This method of visually integrating the sub-components that comprise a domain is a generally applicable instructional methodology for lower the sum attentional cognitive load and enhancing cohesive mental model formation for any spatially complex domain that has many sub-components that interact with each other in spatially complex ways to a high degree. This includes but is not limited to Biology, Physics, Chemistry, Calculus Statistics, Accounting, Financial Trading Processes, Data Visualization Interfaces, Computer Science and even aspects

of law, language learning and other domains. More specifically, in physics, the coulomb's force of attraction between electrons, causes kinetic energy of movement which is current in a wire, which creates magnetic fields. These three concepts, coulomb's force, current and magnetic fields should therefore be visualized and taught together in a layered, integrated circuit simulation for maximal retention and spatial understanding of the circuit complex system. In Chemistry, the enthalpy of formation of molecular bonds, valence electrons which create these bonds, L'Chatlier's principle of how bond formation/dissociation drives reactions to create molecular bonds, phase changes and many other topics such as stoichiometry, equilibrium and entropy can all be visualized, integrated, and taught together in a chemical molecular simulation system. In computer science, students should be instructed to use and explore completed computer programs, such as racing games and database driven websites, and to see how the code underpins the various functions of these computer programs and how all the various functions work together in the complete program, instead of learning piecemeal functions without seeing the completed program until the end of the curriculum.

Overall, since even low spatially complex domains, like social studies, can rise to the level of high spatial complexity when enough sub-components are taught with their corresponding interactions, there is literally no system, or domain, that cannot benefit from the incisive application of this integrated visualization learning methodology.

An integrated visualization is one where a visualization for a concept, such as a visualization depicting phospholipids and action potential channels, appears, or "integrates" at each and every instance where it should occur throughout the visualization, such as at each point in the neuron membrane where phospholipids or action potential channels should occur. Also, scientific structures occurs at many layers, such as viewing the neuron membrane at the

wireframe level, viewing it in terms of a series of phospholipids (cellular) and viewing it in terms of a set of molecular structures representing phospholipids. It is important to layer such information so that students can clearly see the link between the various layers of information for the same concept (Kozma, 2003). Accordingly, this study will explore how a lesson on the five steps of signal transmission in the neuron using an integrated visualization of neuronal signal transmission compared to instruction where students view isolated animations of the same material with a wireframe depicting the locations of the neural subcomponents and less detailed verbal interconnections between the subcomponents.

A series of studies by Kozhevnikov, Motes, and Hegarty (2007) has demonstrated students spatial ability is highly correlated with their performance on physics kinematics problems. A study by Wilder and Brinkerhoff (2007), demonstrated that students who view 3d models of protein structure had significant post-test gains opposed to those who did not and many other students demonstrate the visualizations improve biology and overall science learning. While there are numerous studies examining part-whole learning in domains such as lists (Hashner, 1971) and science learning (Mayer & Chandler, 2001), and studies examining the use of fully worked examples for solving math problems (Krischner, Sweller & Clark, 2006; Carroll, 1994), there are no studies currently available which have explored integrated visual external representations in biology learning, or in *any* domain.

The theoretical background of this study is grounded in theories of mental models, visuo-spatial long term working memory and central executive modulated attentional cognitive load. Specifically, this study is concerned with mental models of physical systems, which are internal representations of the external system (Gentner & Stevens, 1983). Creating and manipulating mental models of complex physical systems, here signal transmission in the neuron, a great deal

of attentional capacity to activate and integrate the essential visual, haptic, auditory and other required representations to understand this complex system in the long term memory of students. Cognitive load theory (Sweller et al., 1994) states that individuals need to reduce unnecessary mental load because memory capacity is limited (Baddeley, 1992). Under the Cowan (1988) model, cognitive load is framed in terms of the attentional capacity required to temporarily attend to the requisite information in long term memory.

Following from the theoretical model behind this study, it is predicted that students shown detailed integrated wireframe and cellular level stop frame animated videos of the major neural subcomponents involved in signal transmission in the neuron will perform significantly better on free response questions and diagram questions than students shown isolated stop-frame wireframe and cellular level animated videos of the major neural sub-components involved in signal transmission in the neuron along with the locations of the subcomponents on a wireframe of the neuron and less detailed descriptions of their interconnections. This is because the overall (internal + external) central executive modulated attentional cognitive load in long term working memory of encoding the integrated neuron lesson is less than the attentional cognitive load of encoding the neuron lesson where only isolated subcomponents are depicted.

Overview of the Dissertation

This dissertation is organized into five chapters. Chapter II provides a review of the literature relevant to this research, including the benefits of the Cowan Long Term Working Memory framework over the Baddeley framework and the implications for cognitive load theory for isolated and integrative neuroscience visualizations. In addition, Chapter II concludes with hypotheses that arise from the Virk Long Term Working Memory framework for learning from isolated and integrative STEM visualizations.

Chapter III presents a pilot study that investigated how students presented with isolated versus integrated cellular and molecular layered neuroscience animations differed in free response questions based on the neuroscience material presented to the integrated group.

Chapter IV presents a dissertation study that focuses the pilot study on the cellular neuroscience information and fixes the time on task confounds of the pilot. In this dissertation study, the performance of students shown isolated cellular animations of neural signal transmission were compared to those shown an integrated animation for the information presented equivalently to both groups on free response questions and diagram labeling questions. Retention for the neuroscience information presented non-equivalently only to the integrated group was also measured.

Chapter V provides a summary of the results and relates the empirical findings to the Virk Long Term Working Memory framework. The limitations of the studies, the theoretical contributions, and the practical implications are also discussed. Chapter V concludes this dissertation with possible directions for future research.

CHAPTER II

LITERATURE REVIEW

I. Mental Model Acquisition and Viewing Animations of Neural Signal Transmission

Individuals use mental models to understand real or imaginary situations (Seel, 1989). Theories of mental models include theories of mental models of logical reasoning (Johnson-Laird, 1983) and mental models of physical systems (Gentner& Stevens, 1983). Johnson-Laird's models generally refer to internal models of premises students create when engaging in logical reasoning tasks, such as solving syllogisms. Here, students determine is a syllogism is accurate by generating a mental model that satisfies the premises, and then seeing if the conclusion of the syllogism is "present" in this mental model. Overall, Johnson-Laird's mental models tend to be a spatial layout of entities, such as the various cellular and molecular entities which comprise the neuron and are used during signal transmission.

A second construct of mental models has been proposed by Gentner and Stevens (1983), mental models of physical systems. Here, mental models of physical system consist of spatially organized entities that have functional relations among the various entities, such as how increasing the amount of calcium at the dendrite will increase the rate at which the action potential occurs at the axon hillock. Tsuei, Hachey & Black (2004) enumerated five core characteristics of mental models of physical systems: they are dynamic, imagistic, entities are causally connected, have entities which are laid out spatially and can be "run" in the mind's eye.

These two types of mental models have many similarities. Researchers advocating for both models agree that internal mental models mirror the external structures they represent. Johnson-Laird (1983), states that the "structures of mental models are identical to the structures of the state of affairs, whether perceived or conceived, that the models represent" (p.419).

Importantly, under both constructs of mental models, mental models enable students to make inferences and predictions, for example a students mental model of animations of signal transmission in the neuron will enable him to make inferences about how the various steps in signal transmission are related to one another (Johnson-Laird, 1983; Williams et al., 1983).

According to de Kleer and Brown (1981b) there are two stages involved in the construction of mental models of physical systems, 1. understanding how the entities in the physical system interact to produce behavior, like understanding how neurotransmitter binding to a dendrite causes calcium channel nearby to open, and 2. establishing a sequential chain of these causal events, such as understanding what stages come before other in the signal transmission in the neuron.

Here, we are concerned with both mental models of reasoning and physical systems, as the process of signal transmission in the neuron depends upon both 1. understanding the spatial layout of the various cellular and molecular sub components involved and 2. understanding the functional relations between groups of sub components that are causally related, for example, how sodium that influxes from the axon hillock causes a subsequent set of sodium channels to depolarize.

II. Baddeley's Model of Working Memory vs. Cowan's Model of Long Term Working Memory

There are four components to working memory under Baddeley's (19992; 2000) model: a central executive, episodic buffer, articulatory loop and visuo-spatial sketchpad. The central executive is responsible for directing attention to relevant information, suppressing irrelevant information and inappropriate actions, reasoning and managing the operations of the visuo-spatial sketchpad, phonological loop and episodic buffer. The phonological loop maintains

actively orated verbal information and prevents its decay by articulating its content silently, such as the audio that accompanies visual animations of signal transmission in the neuron.

Important to this study, the visuo-spatial sketchpad temporarily forms/activates, stores and manipulates spatial and visual information. It is comprised of a visual subsystem that processes shape, color, and texture, the *visual cache*, as well as a spatial subsystem that processes information related to location and movement and rehearses the visual information in the visual cache, the *inner scribe* (Logie, 1995). Maintaining visual images in the visuospatial sketchpad and processing them are two processes that compete for a limited quantity of cognitive resources (Just, Carpenter & Hemphill, 1996). Accordingly, if a person successfully visualizes a complex system, such as the various components and steps involved in the complex system of neural signal transmission, they may still lose part of the image when they attempt to transform the image, such as visually integrating the neural sub-components throughout the visual model. Also, the act of visualizing a complex system, such as signal transmission in the neuron may take up so much visuo-spatial working memory resources that the person may have no capacity left for manipulating the image at all.

The episodic buffer integrates verbal information from the phonological loop and visual information from the visuo-spatial sketchpad to create a cohesive mental representation of the synchornized incoming information. The episodic buffer also assists in transferring the information from both stores of working memory to long term memory thru the process of consolidation, although Baddeley is not very clear as to how this occurs or whether the two memory stores are also engaged in the consolidation process.

Cowan (1988), rejects Baddeley's assertion that incoming visual and verbal information is processed, maintained and transformed in separate and distinct stores. Instead, under his long-

term working memory model, he proposes a model where there are only two components: 1. A long term memory repository of previous information where this information can be temporarily in an activated state, where some of this temporarily activated information. Three to five (3-5) chunks of information, where a chunk is a set of information bits the perceiver recognizes as related in some manner based on their long term memory representations, that are encoded as an integrated, grouped, representation, receive the highest level of attentional activation in the *focus of attention* via operation of the 2. central executive the second component. The central executive operates similar to the Baddeley model to direct attentional resources used cognitively to activate, maintain, manipulate, and integrate information activated within long-term memory, with the strongest activation directed to information within the focus of attention. By chunking information, whether visually, haptically, echoically or via any other modality, humans get attend to more information in the foci of attention than the proposed 7 +/- 2 items of information, by chunking the information into 7 +/- 2 grouped chunks of these individual information bits (Miller 1956).

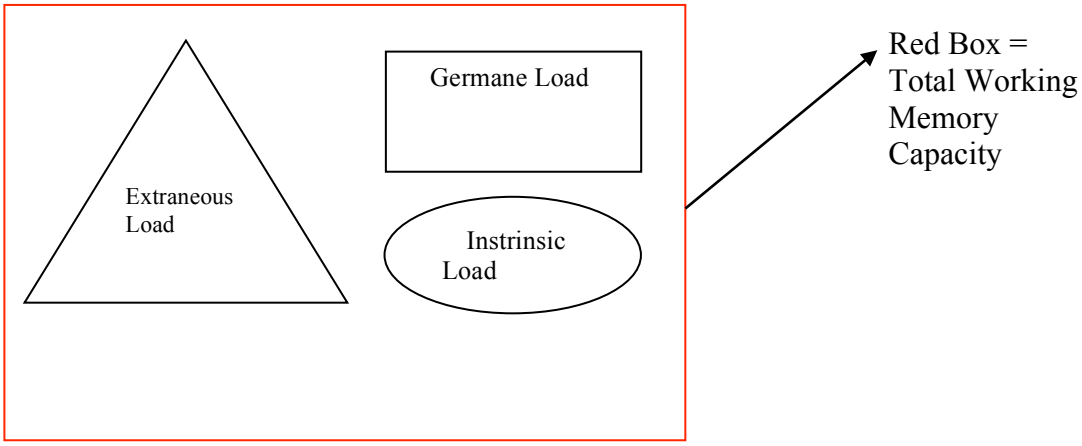
Cowan's focus of attention essentially operates like a domain-general working memory store, where information can be activated, maintained and processed from any of the five modalities, verbal, visual, haptic, olfactory and gustatory information. It is important to note that Cowan's model provides for modalities not accounted for by the Baddeley model, haptic, olfactory and gustatory information within long term memory. Also, here Cowan does not assume there is a consolidation process where information stored in working memory is transferred to a long term memory store, but also does not enumerate how incoming, novel information is sufficiently rehearsed and activated in activated long term memory that it becomes part of long term memory.

III. Cognitive Load Theory under the Baddeley Model Working Memory

Cognitive load theory (Sweller et al., 1994) states that individuals need to reduce unnecessary mental load because memory stores, like visuo-spatial memory, are limited in capacity. Under CLT, three sources of cognitive load, intrinsic, extraneous, and germane, cause mental strain during learning from a series of science animations. Under CLT theory, intrinsic load cannot be reduced and is an inherent property of the information to be taught, here neural signal transmission animations. Under an intrinsic cognitive load theory, the complexity of a complex scientific system is determined by 1) the number of entities or components that comprise the system and 2) to what degree these components interact with one another. Unnecessary mental demands created by the way in which information, such as animations of five steps of neural transmission, is presented is called *extraneous load*, and can be reduced by presenting the information in a more efficient manner, such as integrated five isolated animations into one complete, integrated visualization. The last form of cognitive load is *germane load*, which is the mental load that used to acquire schemas, a cognitive framework or concept that helps organize and interpret information (Piaget, 1928). Here, germane load is derived from creating a complete schema of how signal transmission in the neural occurs which would require integrating isolated animations of the five steps of signal transmission by chunking them together.

By way of the additivity hypothesis, the summed instrinsic, extraneous and germane loads cannot exceed the student's maximum working memory capacity in order for learning to occur (Paas, et. al, 2003).

Learning Occurs Entirely :



Learning Does not Occur Entirely :

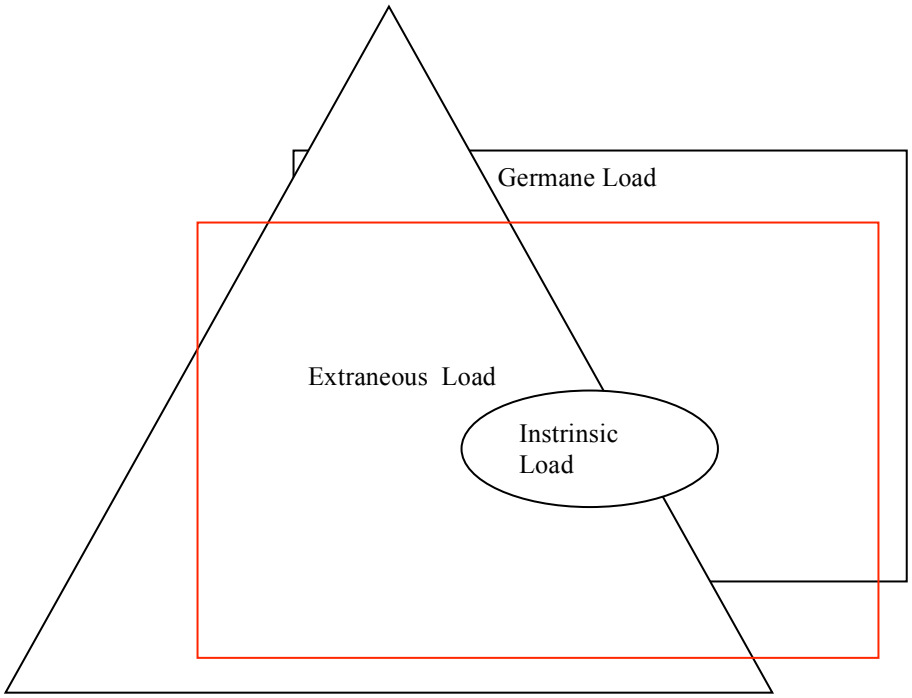


Figure 1: Diagram of Cognitive Load Additivity Hypothesis

Accordingly, the intrinsic load of neural signal transmission material, the extraneous load created by the mode of presenting animations of this material such as whether the animations are isolated or integrated, and the germane load of relating the information contained in the neural animations to previous knowledge in long term memory in order to create a schema of signal transmission overall, cannot exceed the working memory capacity of the student viewing said neural animations, otherwise they will not learn all of the signal transmission material as evidenced by incorrect responses on assessment questions.

One method of reducing students' cognitive load is to present material, such as neural signal transmission material, in both verbal and visual codes. Under Paivio's dual-coding theory (DCT), information that can be processed in both verbal and visual processing systems will result in improved memory and comprehension for the material. This is because there are two codes, both verbal and visual, that point to the same information in memory and two sets of cues, linguistic and pictorial, that point to the same information during retrieval. Here, providing students with visual animations of signal transmission in the neuron as well as auditory accompaniment that explains the animations provides them with both verbal and visual codes and cues and reduces the cognitive load of processing neural signal transmission material.

IV. Learning via Animation

Animations can have a supplantation effect, where they help students' perform cognitive processes they would be unable to perform without the animation (Salomon, 1994). Mayer (2001) describes animations as having a facilitating effect, meaning that due to a reduction in cognitive load from not having to internally generate imagery because it is present externally via the animation, cognitive off-loading, cognitive processes that were possible but required a large amount of working memory resources, such as seeing the interrelations between various steps in

signal transmission in the neuron, now take less working memory resources to complete. Animations also have an enabling function, where also due cognitive off-loading by the animated external representation, processes that normally would be impossible to complete, are now possible, such as perceiving interrelations between various steps in signal transmission in the neuron that are so spatially complex that they are very difficult for most students to perceive without an explicit visualization. For example, it has been found that students have an easier time observing the rotation of the Earth and movement of an object in an animated simulation than to perform the corresponding mental simulations on his own by using just a static picture (Forbus, Nielsen & Faltings, 1991).

However, for students who can perform mental simulations/manipulations internally, the external cognitive support that animations can offer may hinder their learning (Schnotz & Rasch, 2005), and hence animations should be used to help students process information primarily when processing the information from text, static pictures, or isolated, unconnected animations results in a cognitive load that is higher than their zone of proximal development, or the range between the lower limit and upper limit of task difficulty. For example, animations used to explain the five steps of signal transmission in the neuron should be used primarily if processing these steps from static pictures or text results in a cognitive load that is outside the zone of proximal of most students. Similarly, giving students integrated animations of the five steps of signal transmission should be used if processing the interrelations among five isolated animations of signal transmission in the neuron requires a cognitive load that is outside the zone of proximal development of most students.

Animations can be advantageous over static pictures because it allows the user to visualize information which changes over time (Rieber, 1990). However, Schnotz and Rasch

(2005), also found that different kinds of animations serve different functions. Animations that are used to display a large number of static pictures and show different states, tend to enable students to perform more cognitive processing that they would normally be able to. Animations allowing the display of dynamic processes tend to have a facilitating function, by making mental simulations easier to perform due to the reduction in cognitive load. Here, animations of neural signal transmission that show key states in the steps of signal transmission, and are more like a series of a fairly large number of sequentially presented static pictures depicting different key states in neural signal transmission, than a dynamic animation the sequential steps of neural signal transmission that displays the continuous movement of neural entities, such as calcium ions or neurotransmitters as they would move in real time in an actual neuron. Hence, animations that show a series of sequential static pictures of signal transmission in the neuron are likely to have more of an enabling effect on students than a facilitating effect.

Students with higher prior knowledge, such as more background in neuroscience, should benefit more from the enabling functions of animations, while students with lower prior knowledge, such as having taken few if any courses in neuroscience, should benefit more from the facilitating function of animation, such as animations of signal transmission in the neuron (Schnotz & Rasch, 2005). It is noted, that Schnotz does not purport that students with low background knowledge *simply do not benefit* from the enabling function of animations, rather that higher knowledge students may benefit more, the likely scenario being that both high and low prior knowledge students both significantly benefit from the enabling function of animations but to different degrees.

Visual images with Narration versus Text, why are Narrated Visualizations so Important ?

Students who listened to a narrative explaining how a bicycle pump works remembered only half of the bicycle pump process and had great difficulty transferring the information to new problems (Mayer & Anderson, 1991). In contrast, in accord with Paivio's (1986) dual coding hypothesis, students who watched an animation of the bicycle pump process along with hearing the narration, thereby receiving both visual and verbal codes, performed significantly above the narration-only control group, with an Cohen's d effect size of over 1. Mayer refers to this as the *multimedia effect* that students learn better from animation and narration, than just narration alone.

Under Mayer's (1997), cognitive theory of multimedia learning, students 1.select relevant words and images for further processing in working memory, and possibly convert verbal codes into visual codes or visual codes into verbal codes when necessary 2. take the verbal and visual codes in working memory and organizing them into verbal and visual models, 3. integrating the verbal and visual models into one coherent mental representation and with the students' prior knowledge in the domain. Implicit in this model, is that the process of integrating verbal and visual models and codes can happen asynchronously, and this does not need to be a necessarily linear and rigidly segmented process, where some verbal and visual codes may be integrated immediately opposed to after being processed separately into distinct verbal and visual models of the information.

Animations vs. Static Graphics

Spatial and temporal relations and concepts in a content domain that cannot be explicated by texts can be made visually explicit to the student thru static pictures and animations, here a series of animations depicting the steps of signal transmission in the neuron (Stenning, 1998).

However, many studies have demonstrated that animations and static graphics that show change over time do not have significant differences in learning gains across a broad variety of content areas (Tverksy, Morrison, &Betrancourt, 2002). Many studies that purport to show a difference between animations and static graphics compared animations to static graphs and text that did not contain the same information, or included animations that had interactive elements such as stop, start and reverse buttons, that were absent in any form from the control conditions. Accordingly, in the proposed study, dynamic animations that "tween" the movement of entities that move along various paths in the neuron (such as the Sodium ions flowing in the neuron), are not used, instead a sort of "stop-frame" animation is used to display the motion of neural entities, which the animations are more like a series of static key critical states of movement threaded together, than a continuous dynamic animation.

Visuo-spatial reasoning and science learning

A series of studies by Kozhevnikov, Motes, and Hegarty (2007) has demonstrated students spatial ability is highly correlated with their performance on physics kinematics problems. Another study by Hegarty, Kris, and Cate (2003) demonstrated that students' understanding of mechanical systems was enhanced by external visualizations, whether static or animated. A study by Wilder and Brinkerhoff (2007), demonstrated that students who view 3d models of protein structure had significant post-test gains opposed to those who did not and many other students demonstrate the visualizations improve biology and overall science learning. Several other studies in the domain of biology attest that visualizations improve learning.

V. Part-Whole Learning and Worked Examples in Problem Solving

There is a strong body of research examining part-whole learning in domains such as lists (Hashner, 1971). However, here the parts are not building blocks of the whole, rather participants

chunk the individual list entities by finding relations among list items which aren't particularly related. Hence the parts cannot be "integrated" to make a greater whole, as the individual items in the lists are not subparts to a greater whole, but merely distinct list items.

Mayer & Chandler (2001), did a study on presenting students with a series of static pictures depicting the process of lightening. The parts-only (P) presentation consisted of students viewing each static picture and hearing its narration individually for the 16 steps of lightening formation, and clicking a button to move from segment to segment. The whole presentation (W) consisted of showing the students all 16 lightening process segments at once. Participants were shown the lightening presentation twice in one of four formats (PP, PW, WW, WP), and differences were found among the four groups on various measure of recall and transfer. However, note while here the various segments that comprise the 16-step presentation on lightening formation do make up the whole, that is the entire presentation on lightening formation, but each individual segment is still not a sub-part of lightening formation that can be integrated to generate an entire visual model of lightening formation. Rather, each segment displays various states of ions, water and air that comprise various stages of how the dynamic process of lightening formation is caused by transformations and causal interactions of these three basic entities. Contrast this multimedia presentation with the proposed study which entails subjects viewing a series of separate videos on neural signal transmission where in each a subpart of the neuron, like the dendrite, or phospholipid is explained, and the students needs to assemble these subparts to create an integrated, integrated mental model of signal transmission.

Many studies have been conducted examining the use of fully worked examples for solving math problems (Kirischner, Sweller & Clark, 2006; Carroll, 1994). These studies generally involve given students in one group a packet of worked examples for a specific topic

such as solving geometry angle problems, and students in a second group the same problems, but now they are not worked out, the students must solve them. Results generally show significant differences between the worked example and problem solving groups, where the worked example group performs better than the group that only solves problems without the worked examples. Again, here the individual worked out problems, for example worked out geometry problems, are not distinct and critical sub-elements of the concept being taught. Instead they are various instantiations of geometry problems in various geometric contexts, that when taken together provide a more flexible and rich mental model of the concept, but in themselves are not various components of the concept. Also, worked examples research extends to the solving problems in various complex domains (math, science), but does not extend to how people understand straightforward science content, where the goal is not to solve problems but rather to achieve depth of understanding and a rich mental model of the content at hand.

VI. Gaps in Previous Literature on Mental Model Acquisition, Cognitive Load, Working Memory Modeling, Part-Whole Learning, Visuo-spatial cognition and Multimedia Science Learning

Examining the previous literature we see that there are no cognitive models whatsoever of mental model acquisition and cognitive load theory framed in terms of Cowan's Long Term Working Memory, focus of attention Model.

Also, examining the previous literature in part-whole learning and worked examples research, we find that there are no studies that examine how well students can assemble various conceptual parts of complex scientific system presented in isolation, such as the sub-parts of the neuron like the dendrite, sodium channels or phospholipid, by chunking these sub-components, versus providing students with models where the various sub-parts are already assembled into

the whole scientific system and they observe the processes and interactions and sub-parts, an *integrated* visualization.

An *integrated* visualization is one where a visualization for a concept, such as a visualization depicting phospholipids and action potential channels, appears, or "integrates" at each and every instance where it should occur throughout the visualization, such as at each point in the neuron membrane where phospholipids or action potential channels should occur.

Hence, in order to make a fully integrated visualization for an abstract concepts, three key steps must occur (these steps comprise an *integrated visualization algorithm*) :

1. Identify specifically which abstract concepts in the domain need to be visualized (here, the various sub-elements of the neuron, such as the dendrite channels, phospholipids, calcium channels, calcium ions, sodium channels, etc.)
2. Create visualizations that depict each abstract phenomenon, using visual metaphors if needed, being sure to capture dynamic changes in quantity over distance (static pictures and semi-dynamic animations of the various neural sub-elements)
3. "Integrates" the visualizations you created in (2) of the abstract concepts in the model you are using to teach the domain, by displaying the visualization *every time* it occurs in the model, adapting the visualization as needed every time you display it, so it makes sense in the context of every instance where it is displayed (displaying the phospholipid every time is appears along the neuron membrane, displaying the sodium and potassium channels at every break in the myelin sheath in the axon and displaying them at both the top and bottom of the neuron, etc.)

Neuroscience is an ideal seminal domain to test of efficacy of integrated versus isolation visualizations, as it is widespread domain most students learn in high school and undergraduate

colleges, that has many spatial complex relations that are the byproduct of various neural subparts interacting with each other.

There are no studies framing visuo-spatial cognition as a whole, and more specifically visuospatial cognition in the context of complex scientific domains, such as neuroscience, in terms mental model acquisition and cognitive load theory framed in terms of Cowan's Long Term Working Memory, focus of attention Model. Furthermore, the main question of interest for this study, how isolated versus integrated multimedia visual external representation of the sub-parts of complex scientific domains can *cognitively facilitate* science learning, has also not been studied *at all* in the field of visuos-spatial cognition.

*It is duly noted, that studying isolated versus integrated multimedia presentations of visual external representations of sub-parts that comprise a complex domain is absolutely critical to advance the field of external representation design for complex domains, *cognitive engineering*, as assembling sub-parts of a domain into an integrated whole is a potentially very difficult and cognitively demanding process that is crucial for understanding most abstract and complex scientific, mathematical and technical systems.

VII : Proposed Cognitive Framework to Address the Gaps in Previous Literature:

Virk Connectionist Computational Cognitive Multimedia Long Term Working Memory Model for Chunking and Processing Isolated and Integrated External Representations of a Complex Scientific System

Accordingly, in order to address the many gaps in the literature, the current study will examine how students form mental models and cognitively offload from isolated versus integrated multimedia external representations of the sub-parts of the complex scientific domain of signal transmission in the neuron, under the model diagrammed in the current section. In this

proposed computational multimedia long term working memory cognitive model, isolated, non-layered external visual representations, here a set of animated videos detailing the five major steps of signal transmission in the neuron at the cellular and molecular levels sequentially presented, are processed by the retina's cones and rod receptors, esp. in the fovea, and the accompanying auditory explanation for the isolated external visual representation is processed by the auditory sensory system, the hair cells, cochlea and associated ear organs. In the next step we will see how this visual and auditory information will cause various brain systems and the central executive to activate various representations in the long term memory store to various degrees, specifically :

V : occipital cortical visual representations

A : temporal cortical auditory representations

M : somatosensory cortical Motor/Haptic/Proprioceptive representations

O : Olfactory representations

G : Gustatory representations

R : Other representations, such as emotions and prefrontal cortical cognitive reasoning processes

Figure 2: Connectionist Framework for Multimedia Learning in Long Term Working Memory

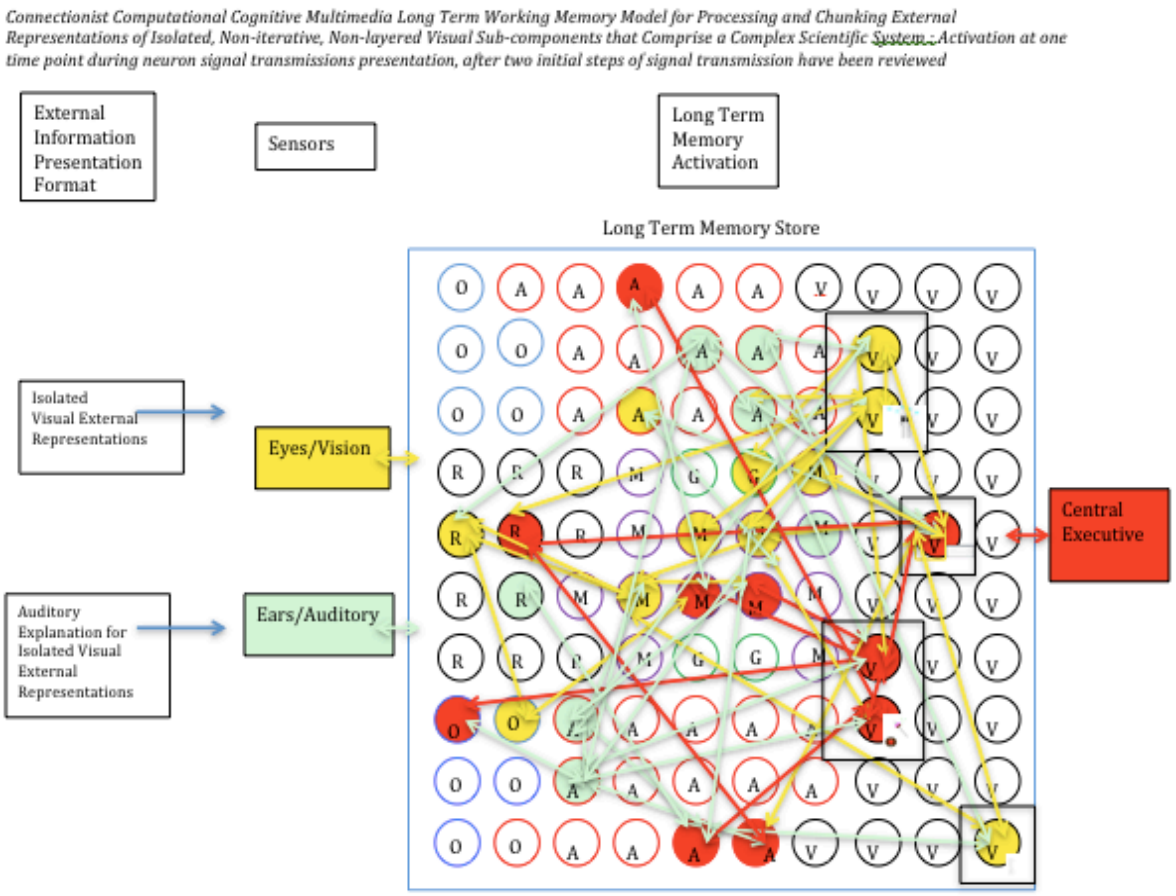


Figure 3: Connectionist Framework for Isolated Neuroscience Multimedia Learning in Long Term Working Memory

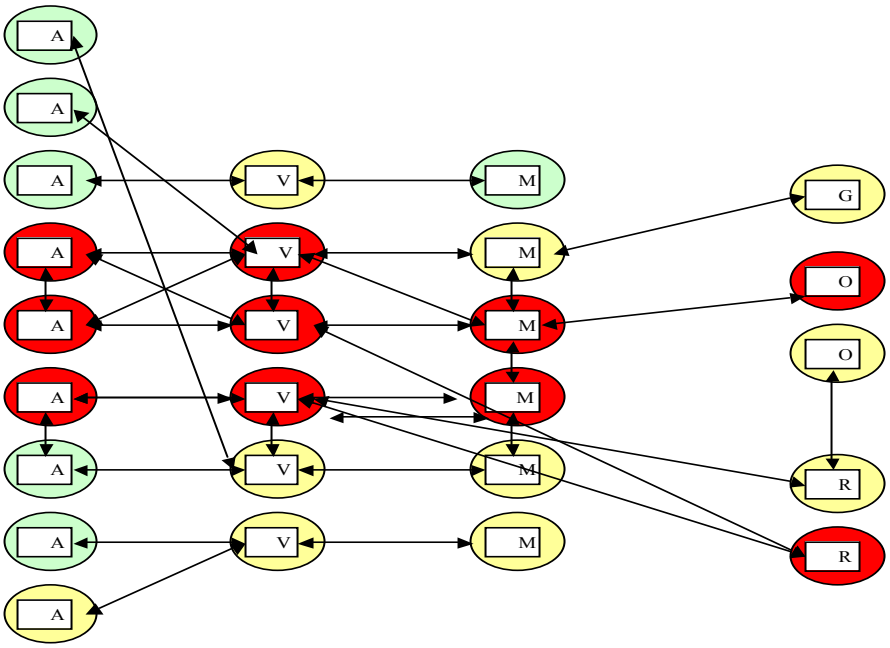


Figure 4: PDP Framework for Isolated Neuroscience Multimedia Learning in Long Term Working Memory

Under Cowan's Long Term Working Memory Model, after visual and auditory information is processed by their respective sensory systems, retinal signal data from the isolated visual external representation, the series of animated videos detailing the five major steps of signal transmission in the neuron sequentially, bi-directionally activate visual (V), haptic/motor (M), auditory (A), gustatory (G) and olfactory (O) and other representations (R) in long term memory (marked in yellow and with yellow arrows). There are separate stores for these modalities under the Cowan model as in Baddeley's model, but these stores are distributed throughout the cerebrum. All of the various representations once activated will propagate to related visual, verbal, haptic, olfactory and gustatory representations thru interconnected propositional networks (Anderson, 1980).

The arrows (green representations activated by vision, yellow for representations activated by auditory stimulus) here are bidirectional because activated representations (visual, auditory, etc.) that are connected to one another, *chunked*, constantly influence and shape each others activation, there is continuous, statistical, real time cross talk amongst all connected representations in long term memory during the neural signal transmission presentation and afterwards during consolidation and subsequent recall.

Most of the activation is concentrated towards visual representations, as this is the primary form of processing for visual stimuli, where the visual processing that occurs is similar to the processing done by Baddeley's visuo-spatial sketchpad, this is why most of nodes activated (yellow) are visual nodes. The second most activation will likely be somatosensory codes, esp. haptic codes (touch/pressure) as visual and haptic codes often cross-integrate (Ernst and Banks, 2002). In addition, somatosensory codes also include pain, temperature, proprioceptive codes, which may also be activated to some degree by the visual stimuli.

For example, if a student views the first animation of neurotransmitters binding to a dendrite, and also learns what a phospholipid looks like, in addition to where these structures are located spatially on an overall wireframe of the neuron:

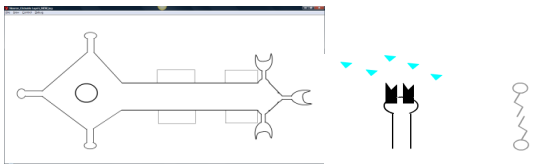


Figure 5: Examples of Key Neuroscience Instructional Images

Visual representations and schemas such as previously encoded memories for shapes that frame the objects in this animation (wireframe: diamonds, tubes, spatial protrusions, neurotransmitter : triangle, dendrite receptor : fork-like shape and rectangle, dendrite : cylinder with a nob, phospholipid : circle and zigzags), colors (blue, black, grey), objects fitting into holes lock and key and triggering a door opening (neurotransmitter binding to dendrite, which causally causes calcium channels to open later), objects moving (neurotransmitter migration to dendrite receptor) are activated. Also, the haptic feel of what a neuron wireframe might feel like (perhaps like what an actual wire feels like) and what it feels like for a key to lock into a keyhole, might be activated when the neurotransmitter "snap" into their respective place at the dendrite receptor to scaffold the corresponding visual representation. It is conceivable on some level a viewer may associate smells, perhaps something that smells like rubber because of all the black and grey used, or taste sensations, for example what a tic tac tastes like because the neurotransmitters resemble them, with the visual animation of neurotransmitter binding. For the sake of depicting this cognitive model completely this is assumed in the model presented, but is it likely few students actually associate smells and taste with the neural signal transmission videos they view. Also, when a student watches the neurotransmitter binding video, they may reason about what they are viewing and try to figure out where the neurotransmitter come from, or what

does binding to the dendrite cause and why, hence they may actively process the information using prefrontal reasoning schemas (R node).

The arrows from the eyes/visual sensory system to long term memory representations are bi-directional, as what the person is viewing influences what representations are being activated, and what representations are being activated, influences what elements of the visual stimuli the person decides to focus on or filter out by changing the orientation of their head, or the position of their retinas by contracting and relaxing their ocular muscles.

For example, as the student attends to the key areas of the wireframe and animation thru saccades and directed visual attention, such as the areas on the wireframe where the dendrites occur and where the neurotransmitters are and where they bind, they move their eyes to shift ocular focus, and by shifting ocular focus alter their internal visual representation of what the wireframe, neurotransmitter and dendrite look like, making them more clear, sharper in color and possibly bigger.

Clearly, auditory information primarily will activate auditory codes in the temporal cortex, for processing of the incoming sounds. The processing done here is similar to the processing done by Baddeley's phonological loop. As Johnson-Laird (1983) points out, verbal information can cause individuals to create visual and spatial mental models of the information being processed using a mechanism similar to Baddeley's visuo-spatial sketchpad. The auditory explanation here directly narrates the images and motions of the visual external representation, there is a one to one mapping with little auditory/verbal information that does not directly map onto the visual images and motor representations that scaffold the visual representations. The auditory codes evoke are likely to be precisely directed to help process, attend and categorize more efficiently the current external visual representation being viewed and any associated motor

codes, instead of used to evoke internal imagery and motor codes that are different from what is being viewed. Hence we see in the diagram that the green arrows for the auditory explanation stimulus mostly map onto representations very similar and congruent to the representations activated by the visual external representation.

For example, after hearing and seeing where on the wireframe dendrites occur, a student viewing the neurotransmitter binding to dendrite animation discussed previously, will hear auditory explanation below:

> STEP 1
> STRUCTURES :
> Throughout the neuron are these structures, which are phospholipids.
> Each phospholipid is comprised of a phosphate head and a tail of carbon and hydrogen that extends from this head.
> These phospholipids line all the structures of neuron
> These neon blue structures are neurotransmitters
> These black structures are dendrite receptors.
> <play animation>
> The first step in the action potential, is that neurotransmitters released from a neuron nearby move towards the dendrite receptor and bind to the dendrite receptor.

As you can see, the verbal narration directly maps to the animation they are viewing, as various visual aspects of the animation such as the phospholipid head structure, color of the neurotransmitter, and spatial aspects, such as neurotransmitters moving towards the dendrite are orated. The verbal narration activates the corresponding auditory codes in the temporal cortices, and also helps cognitively offload the strain of categorizing the visual objects in the dendrite animation, by doing some of this categorization for the viewer verbally. Hence, the auditory codes map directly (arrows connect) onto most of the visual codes activated by the dendrite animation and the motor codes activated via the visual imagery depicting neurotransmitters binding to the dendrite.

As with the visual codes, it is conceivable either in isolation or in concert with the visual codes the auditory codes are mapped to, that novel visual representations, independent of the visual imagery shown to the student, are activated in addition to novel auditory, motor, gustatory, olfactory and other representations (R). *For example, hearing the word "receptor" may activate a visual image of a receptacle for plastic bottles, not depicted in the animated neurotransmitter visualization, or another word, perhaps "receiver", and possible other modalities associated with the word.*

Auditory activation arrows here, as with visual stimuli, are bidirectional, as auditory stimuli affects what representations in long term memory are activated, and what representations are activated affects how a person directs more or less attention to what they are hearing, and possibly their head to position their ears more efficiently for hearing. *For example, when hearing the pitch of the narrator describing how neurotransmitters bind to the dendrite, the listener may subconsciously alter the position of their hair cells to more effectively pick up on this pitch and may direct more auditory attention to phrases they think are important, which in turn makes their auditory representations more precise and coherent.*

The student may also actively use prefrontal representational strategies, such as actively making analogies, to generate, and engineer novel internal visual, verbal, gustatory, olfactory and auditory representations and transformations, not explicitly visualized or orated by the animated signal transmission videos, to scaffold their understanding of the isolated visuals and accompanied auditory explanation while viewing and hearing them. *For example, a student viewing the neurotransmitter dendrite binding animation, may actively try to construct an image (and associated representations of other modalities) of an analogous system, such as key fitting into a lock and the haptic feeling of tightness when the key fits into the lock (motor code), and*

imagine superimposing this lock and key image over the neurotransmitter animation to help them remember what it means.

Visual images that connect to each other causally and structurally, here where the dendrites occur, shape of the dendrite receptors, neurotransmitters and dendrite bouton are wired, or chunked together, to some degree, under the traditional Hebbian paradigm (1949) that neurons the fire together, wire together. Hence in the diagram we see that there are some visual nodes which are connected to one another with bidirectional arrows, representing chunks of visual information that are wired together for more efficient coding. Any auditory connections or connections with other modalities, such as motor codes or olfactory codes, for the visual nodes are also included in this chunk. *The diagram above represents a point in the presentation where the viewer has seen two of the cellular signal transmission animations, 1. for the neurotransmitter receptor binding to the dendrite, 2. The phospholipid, and 3. One for calcium ions entering calcium channels at the soma in conjunction with being shown where these structures occur on the neuronal wireframe.*

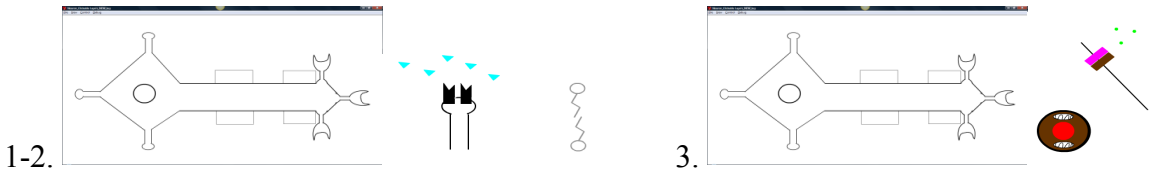


Figure 6: Screencaptures of animations of first two steps in signal transmission process

Accordingly, in the diagram above, we see four chunks of visual nodes (see boxes), one chunk for the wireframe representation, a second chunk for the phospholipid, and a third chunk for the first step of signal transmission (neurotransmitter binding), and a fourth chunk for the second step of signal transmission (calcium ion release) which are also wired to nodes for other modalities, such auditory and haptic nodes and comprise these two chunk subsets in long term memory.

However, these two chunks are not strongly connected, because the animations and wireframe locations they correspond to were presented separately, in isolation. There may be some weak linkages among the chunks, and hence there is only a few yellow arrows connecting the two visual chunks together in the diagrams, instead of many.

The exact nature of what representations the visual and auditory stimuli activate, either in isolation or in concert, and to what degree, will be different for each individual, as each individual has different cognitive memory and attentional (visual, auditory, haptic and other) capacities for processing visual and auditory stimuli, and has a different store of long term memories with which to frame the visual stimuli being processed. However, stated above are the primary expected modality activation trends.

Specifically, aside from the obvious, that a student may have learned the process and sub-components involved in neural signal transmission in a previous course in high school, college and/or graduate school, students will differ in terms of how strongly they encoded the spatial/haptic schemas in their long term memory that frame the four events of cellular signal transmission that are animated for the student, prior to viewing the animations. *For example, if a student has a very strong spatial/haptic schema already encoded for objects snapping in place, like a key snapping into a lock triggering it to open, including what it feels like haptically, especially in terms of pressure receptors, to have a key in your hand and feel it snap into place into the lock and tighten, and many other similar contexts. Hence they will encode the first two steps of signal transmission, neurotransmitters binding into place at the dendrites which subsequently triggering calcium channels to open, more easily, than a student who has a weaker spatial/haptic schema.*

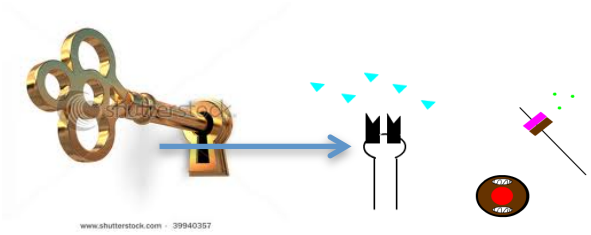


Figure 7: Key to Dendrite Metaphor

Similarly, if a student has a strong spatial/haptic schema already encoded for how discrete objects move in and out of containers, *like people in a room entering thru a door and exiting thru the door, or putting in and taking out marbles from a container, including haptically, what it feels like to physically move a marble in and out of the container opening with your hand, this will give them an advantage compared to students with less developed spatial haptic schemas for how discrete objects move in and out of containers. Specifically, for understanding ions moving into and out of calcium, potassium, and sodium channels, steps 2 and 3 in neural signal transmission, and neurotransmitters being released from synaptic vesicles, the last step in neural signal transmission presented to students.*

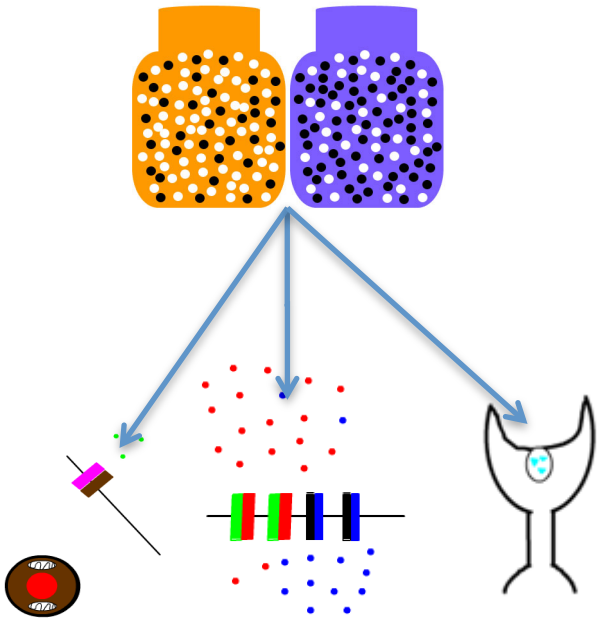


Figure 8: Container to Neural Structure Metaphor

Also, students with higher visuo-spatial processing abilities will be able to attend to more of the visual sub-components on screen and also maintain and integrate previously shown sub-components better than students with lower visuo-spatial processing abilities. *For example, students with high spatial ability will be able to process the visual sub-components of the second step in neural signal transmission, the two sub-parts of the calcium channel and three ions moving into it, faster, more efficiently, using less energy, and will have an easier time maintaining in parallel visual images representing the first step in neural signal transmission, neurotransmitters binding to the dendrites and subsequently integrating and chunking these two representations.* Similarly, using this same example, students with higher auditory attentional capacities will have an easier time attending to the auditory explanation that narrates directly the first two steps of signal transmission, neurotransmitter binding and calcium ion flow and the corresponding wireframes, and also cross-integrating the auditory representations with the visual ones for these two steps.

Central Executive Attentional Processing for Integrating Representations and the Foci of Attention

The central executive directs attention, bi-directionally, to process and integrate, wire together, the multimodal representations evoked by visual and auditory external representations. *The attentional activation is bidirectional because the representations attended to, such as attending to a visual representation of what a calcium channels look like, affects what is attended to, for example, attending to one subunit of the calcium channel visual representation may cause the central executive to then stop attending to this and divert attention to the other subunit of the calcium channel visual representation and vice versa.*

The nodes which are highlighted in yellow and green are in "activated" long term memory under the Cowan long term memory model, and are given a low to moderate degree of attentional activation by their requisite neural sub-systems (visual system for vision, auditory system for sound) and attention-directed cross-representational integration by the central executive.

Nodes in red are in the foci of attention under the Cowan model, which are given the highest degree of attentional activation by their requisite neural sub-systems (visual system for vision, auditory system for sound) and attention-directed cross-representational integration by the central executive. While Cowan asserts under his model that 3-5 chunks of information are in the foci of attention, this is an arbitrary designation, as chunks are arranged hierarchically, where there are chunks within chunks within chunks across a hierarchy. *For example, the visuals and other internal representations depicting neurotransmitters, dendrites, and the spatial movement of the neurotransmitters are all chunked into one representation, but this is also weakly chunked to visuals and other modality representations representing the second step of signal transmission, hence chunking is a highly recursive process, where chunks can be defined across many levels of a chunking hierarchy.* Accordingly, to simply we can assume under this cognitive model information in the foci of attention is commensurate with the amount of information Cowan states consists of three to five (3-5) chunks worth of information. Nodes which are colorless are given no attentional activation by the central executive.

For example, after a student has completed viewed the second step of signal transmission in the neuron, calcium ions flowing thru calcium receptors in the soma, and wireframe pointing out where these structures occur, the major visuals and associated haptic, auditory and other representations encoding the second step of signal transmission are in the viewer's foci of

attention, in addition to some concept of the wireframe and where these structures occur on the wireframe. A student's internal visual, haptic, auditory and other representations of the first step of signal transmission, neurotransmitter binding to the dendrite, location of where the dendrites occur in the wireframe, and the concept of the phospholipid, also explained during the first step, will be in their activated long term memory, but not their focus of attention because the more recently viewed second step of signal transmission takes precedence in terms of attentional resources, and consequently diverts attentional resources from the first step of signal transmission. If the concepts explained in the first and second steps of neural signal transmission were not externally presented in isolation sequentially, but rather together, as an integrated model, more of this information could have entered the foci of attention.

Accordingly the central executive under this model uses attentional resources to chunk the isolated presentations of signal transmission steps and structures into cohesive mental model structures. For example, the central executive would take the viewer's representation of the first step of signal transmission, neurotransmitter binding to dendrite, and the second step of signal transmission, the calcium ions entering the neuron, and chunk these together. Since this takes a lot of visuo-spatial attentional resources, these two steps of signal tranmisssion are only weakly chunked, even after the viewer uses the maximal attentional resources available to him, and hence there is only one yellow arrow connecting them, instead of many.

Similarly, since students are shown where the various structures occur on the wireframe, their representations for these various structures, such as dendrites, neurotransmitters and calcium channels are chunked on some level to their representation of the wireframe via the central executive attentional processes, represented by yellow arrows connecting these representations to the wireframe chunk. Again, this would entail a fair deal of visuo-spatial

attentional resources and accordingly it is predicted only weak chunking would occur, depicting by only having a few yellow arrows connecting these representations of the neural structures to the wireframe, instead of many. The central executive utilizes attentional resources to integrate and chunk other related representations, especially haptic and auditory representations, representing in the diagram by nodes that are connected by arrows in the model. The integration process does not happen linearly, but rather statistically where there is constant cross-talk between the representations evoked by the visual and auditory stimuli which are constantly evolving in lite of the past and present incoming visual external representations and auditory representations. *For example, once a viewer sees the second step of signal transmission, calcium ions entering the soma, this will influence their representation (visual, haptic and other) of the first step of signal transmission, neurotransmitter binding to dendrite, and vice versa, because of the cross-chunking that will occur between the representations of the first and second steps of signal transmission. For example of similar spatial objects such as the dendrite and calcium channels which are both somewhat rectangular in structure being chunked together, that will occur on some level between these representations.*

Colorless nodes, which are not activated represent visual and auditory aspects of the representation the viewer did not encode, *such as perhaps the student only encoded one dendrite binding to neurotransmitters and the corresponding evoked representations, even they the animation depicts two, or perhaps the student did not attend to the auditory explanation and evoked representations explaining the phospholipid because they were distracted by the visual of the dendrite.*

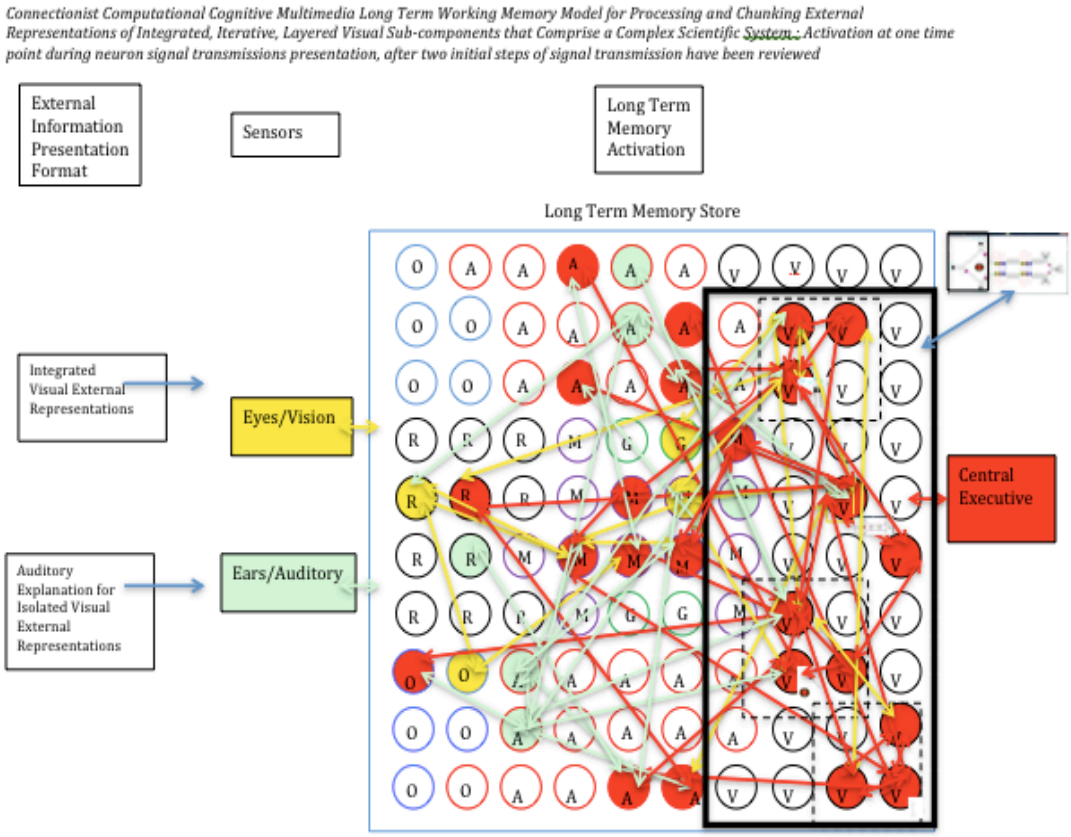


Figure 9: Connectionist Framework for Integrated Neuroscience Multimedia Learning in Long Term Working Memory

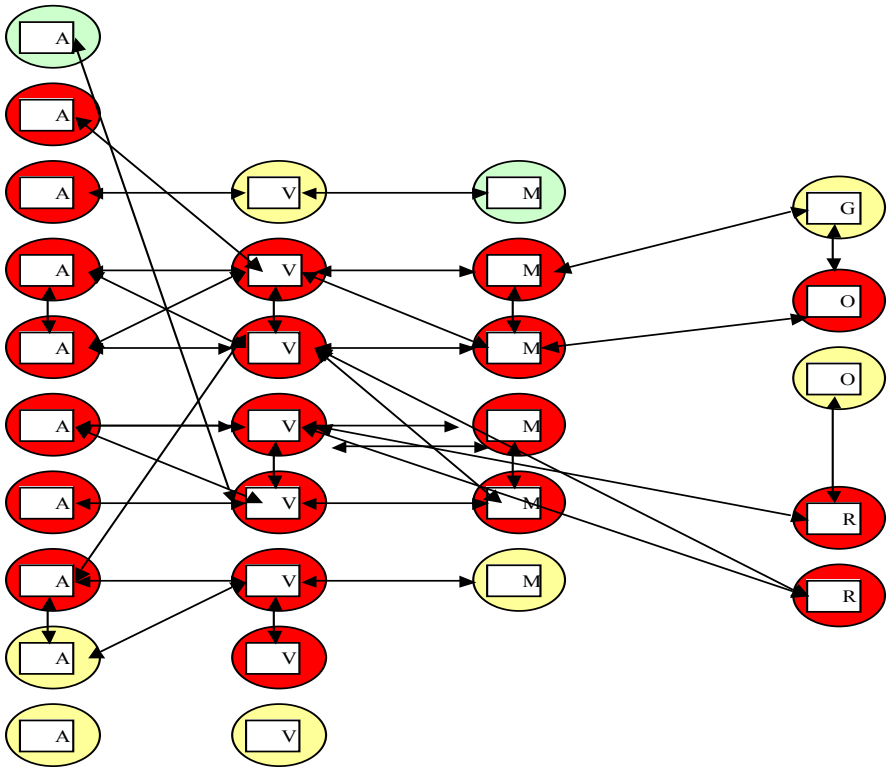


Figure 10: PDP Framework for Integrated Neuroscience Multimedia Learning in Long Term Working Memory

Integrated Visualization Formation

In a presentation where the first two steps of neural signal transmission are represented externally in a format where the neural visual sub-components of the phospholipid, neurotransmitters, dendrites and calcium channels/ions are integrated visually throughout the wireframe

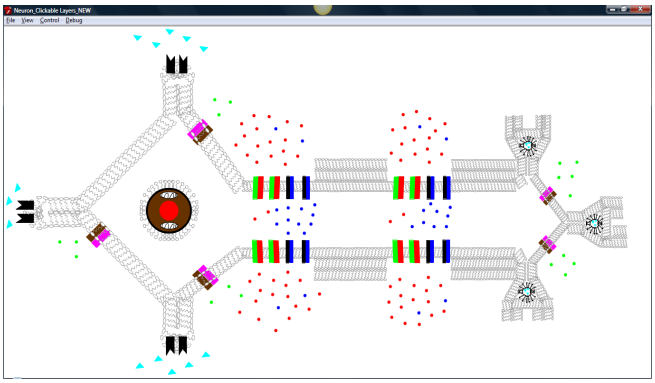


Figure 11: Integrated Neuron

the basic mechanics of how the signal transmission steps are processed are identical to how presenting these steps in isolation are processed (see above section) with certain important exceptions. First, because all of the visual neural sub-components (dendrites, phospholipids) are presented in a visually integrated (the sub-components are duplicated explicitly along the wireframe as they occur, such as the dendrite visually duplicated at each of the three dendritic boutons where it should occur) integrated visual format, the viewer explicitly sees more instances of each of the sub-components, resulting in more visual representation nodes with potentially more corresponding motor, gustatory and olfactory codes. *For example, the viewer sees three instances of dendrites and calcium channels/ions in this model, and hundreds of instances of phospholipids placed along the frame of the neuron. The viewer also would see how the many calcium ions dissipate along the soma to reach the axon hillock, as this is an emergent*

visual property of this visually integrated, integrated neuron external representation. Hence, these additional visual and spatial motions depicted by this model result in more visual representation nodes being activated in the viewer's long term memory.

*Also, it is extremely important to note, that in the visually integrated, integrated multimedia presentation of neural signal transmission, neural signal transmission is explained used a complete visual external representation that has few visual or causal "gaps" in it. Accordingly, the system is completely visualized for the viewer, and this serves to activate very strong spatial schemas that are not as likely to be activated when the neuron is explained using isolated visual, non-integrated representations. *Virtually all of the systems human beings see and interact in everyday life, are completely visible, such as watching a dog run thru a park, turning on a shower and seeing the water come from the faucet and drain into the shower drain or interacting with pinballs in a pinball machine, involve the continuous movement of objects in space that can be followed for periods of time that last from thirty (30) seconds to fifteen minutes or more (15 min.):*

Figure 12: Completely visualized visual systems in everyday life

When we can track objects as they move in space from state to state, we can easily perceive the causal connections among the various time points during the objects movement. *For example, how causally a dog that ran from a tree got to his present location in front of our*

porch, because we saw the dog's bodily movements against the ground which caused him to move across the park and reach our porch.

In addition to many of these events involving the continuous and constant movement of spatial objects, we often experience other modalities in continuity as well. For example, when taking a shower, we feel the constant pressure and sensation of water on our skin throughout the shower and when using the pinball levers, we feel the constant haptic sensation of our hands on the pinball levers. Not all of our daily interactions are so visually and haptically continuously manifest, for example, when we flip a light switch we instantly see a light turn on, but we don't actually see the electrons which causally move thru wires and resistors to generate the light. However, the vast majority of our daily interactions involve interacting and perceiving causal schemas that are visually continuous and also continuous with regards to other modalities for some substantial length of time.

Accordingly, we must have encoded very strong schemas for process continuous events, especially continuous visual motion-based and haptic events in order to efficiently process continuity in our environments. When processing continuous events, we likely are trained to activate chunking mechanisms reflexively to chunk together like visual and haptic properties of what we are viewing, and also discern what is visually and haptically/other modalities different about what we are viewing. *For example, if we watch a dog run continuously along the grass of a park, we chunk that the dog is a constant object and that the grass is a category in our long term memory that we know to activated throughout viewing the dog running across the park in order to more efficiently process this scene. We also are trained to distinguish the dog from the grass as separate cognitive categories, which also aids us in processing this scene. Accordingly, author postulates that humans have strong, reflexive chunking mechanisms that we are trained to*

activate when viewing continuous visual presentations of spatial entities, which stems from our every interactions with spatial objects in movement, such as dogs running along parks, or cars moving continuously along a highway, most of the events we encounter in our daily lives. These strong continuity-based schemas help us to very efficiently chunk external and internal visual information involving movement, and also drastically decrease the attention required to process the visual information and chunk its visual sub-components. When we process a scene that has gaps in it that break our perception of continuity in some way, we don't activate this rich, continuity schemas as strongly, and the attentional load of processing and integrating, chunking, the visual information via the central executive is much higher. Accordingly, since the integrated visualization has few causal or visual gaps in the external presentation of neural signal transmission presented to the viewer, these rich visual, haptic and other continuity schemas are triggered, and this information is processed much more efficiently and utilized less attentional resources.

For example, in viewing the first two major steps of signal transmission and their corresponding visual sub-components, in the integrated presentations are much more integrated in the visualization, and the spatial movements of the neurotransmitters attaching to dendrites, and calcium ions flowing into the neuron are presented both much closer in space, and in time (presented immediately one after another). Accordingly, this continuous presentation is more likely to activate continuity schemas for visual spatial movement of objects to scaffold the processing of these two steps of neural signal transmission. The viewer will then reflexively chunk all the similar sub-components in the model, like the phospholipids that line the membrane, the dendrite channels and the calcium channels and easily distinguish which of these visual sub-components are different, resulting their mental model of the these two steps of neural

signal transmission being much more deeply chunked utilizing less attentional resources in long term working memory.

These additional spatial modes will have additional motor codes associated with them, for example, the haptic sensation of a lock and key snapping together mapped onto a neurotransmitter binding to a dendrite would be mapped three times because the visual for the dendrite was displayed explicitly three times. Also, seeing the calcium ions dissipate and converge spatially at the axon hillock, may evoke a haptic sensation akin to feeling marbles from various directions moving towards a pipe that maps onto the axon hillock. There may be additional (to the isolated presentation representation model) smells (O) and tastes (G) associated with these explicit visuals, such as the smell of marbles and a pipe and the corresponding metallic taste evoked by this integrated presentation. The auditory narrative that corresponds to this integrated visual presentation, is more lengthy, as there are more spatial movements, such as the convergence of many calcium ions moving towards the axon hillock, to narrate, and hence more auditory nodes are activated in this model than the isolated neuron signal transmission multimedia presentation model. As with the previous model, the visual and auditory representations can evoke any of the other representations (V, A, H, O, G, R) in long term memory, and since more representations are being processed externally, as illustrated above, more representations will be activated along the corresponding semantic networks.

As before, the student may also actively use prefrontal representational strategies, such as actively making analogies, to generate, and engineer novel internal visual, verbal, gustatory, olfactory and auditory representations and transformations, not explicitly visualized or orated by the animated signal transmission videos, to scaffold their understanding of the integrated visuals and accompanied auditory explanation while viewing and hearing them.

Importantly, in this visually integrated multimedia presentation, the viewer will likely chunk all of the key components explained and visualized in the first two steps of signal transmission together, represented in the model by a large black box around the nodes representing these neural sub-components, as these components are now presented both spatially (position on screen) and temporally (time between when each concept is discussed) much closer together. For example, the dendrite is juxtaposed to many phospholipids lining its membrane and is close to the calcium channel, all of which are integrated visually onto the same screen, and explained more rapidly in time one after another, instead of being displayed and discussed in large isolated presentations. Each of the three individual neural sub-components presented, the neurotransmitter, dendrite, phospholipid, will still be chunked individually, hence these nodes have dashed boxes around them denoting this, but these three representations will also be chunked very strongly together, creating an emergent spatial representation of the neuron as a whole (similar to the wireframe shown in the isolated presentation). Again, this higher-order chunk is represented by the dark black box around these representations and the multitude of arrows connecting these individual sub-component chunks together, especially among the visual nodes.

Central Executive Attentional Processing for Integrating Representations & Foci of Attention

Here, since the individual sub-components comprising the first two steps of signal transmission are strongly chunked together, especially in lite of the rich spatial, haptic and other continuity schemas that will be activated, hence more information can be attended to via the central executive in the foci of attention then when signal transmission steps were presented in isolation. Accordingly, this entire chunk is present in the foci of attention, since the presentation is being viewed as a continuous chunk of visual information instead of separate isolated chunks.

Not all the representations associated with this massive chunk is in the foci of attention, denoted by nodes that are in yellow and green, and as before some information is never activated in long term memory, hence the colorless nodes.

Also, the central executive need not expend great amounts of attentional energy to integrate and integrate the visual neural sub-components, because there are already pre-assembled for the viewer and represented as a large higher-order attentionally efficient chunk of information, saving a lot of attentional resources as compared to the isolated presentation of these sub-components.

Cognitive Load under Proposed Virk Long Term Working Memory Multimedia Model

The Baddeley and Cowan Long Term Memory Models are similar in that they both have visual and verbal working memory stores, and a mechanism for knowledge integration, chunking, via the episodic buffer/central executive in working memory for the Baddeley model and via the central executive in long term working memory in the Cowan model. The differences are that the Baddeley model does not explicitly provide for haptic, olfactory and gustatory working memory stores, while the Cowan model does, hence Baddeley may assume these modalities are stored in long term memory stores only, and the Baddeley model does not provide for grades of memory activation via attention as the Cowan model does. Specifically, the Baddeley model simply has short term, working, and long term memory, while the Cowan model has grades of attention that span from the most short term memory activation, the foci of attention, to deeply encoded long term working memory activation. Overall, the Baddeley and Cowan models both predict that chunking via detailed elaborations will lead to better recall for the core information presented to both groups, but the Cowan model provides for chunking via the haptic, gustatory and olfactory modalities, and attributes attentional grades of varying activation to each of the concepts being chunked in the neural signal transmission lesson.

Hence, revising the Baddeley Working Memory model of Cognitive Load in lite of the Cowan Long Term Working Memory model, and our proposed computational cognitive multimedia models for processing isolated and integrated visual external representations for complex domains, it is evident that cognitive load is now framed in terms of the attentional processing required to process a multimedia presentation on a given complex domain. Accordingly, the less attention is required to activate visual, haptic, auditory, olfactory and gustatory representations representing a multimedia presentation on a complex domain in long

term memory and to chunk and integrate both information presented equivalently to both isolated and integrated presentations and elaborations upon this information, detailed interconnections, via the central executive, the lower of cognitive load of processing the overall multimedia presentation. Hence, more representations for the information, especially visual, auditory and haptic representations, that be activated within the foci of attention and within activated long term working memory.

Examining again our two presentation modes for the first two steps of signal transmission, isolated versus visually integrated, the visuals of neural sub-components in the isolated presentation (neurotransmitter, dendrites, phospholipid, calcium channels and ions and wireframe), take more attentional resources, and therefore cognitive load, to activate in long term memory than the integrated visual presentation because their isolated presentation does not activate spatial continuity schemas that serve to lower the attentional load of activating the visual sub-components that comprise this information. Also, the isolated visuals are not integrated by definition, and the viewer must expend a great deal of attentional central executory resources to chunk and integrate the four major neural sub-components (neurotransmitter, dendrite, phospholipid, calcium channels/ions) mentally along the neuron wireframe structure in order to form a mental model that is a complete and integrate representation for these two signal transmission steps. Accordingly, fewer representations of the neural signal transmission information from the isolated multimedia presentation are activated in long term working memory store in both the foci of attention and activated long term working memory due to these cognitive load differences, as detailed in the prior section of this dissertation. This model of attentional cognitive load is summarized in the graph below:

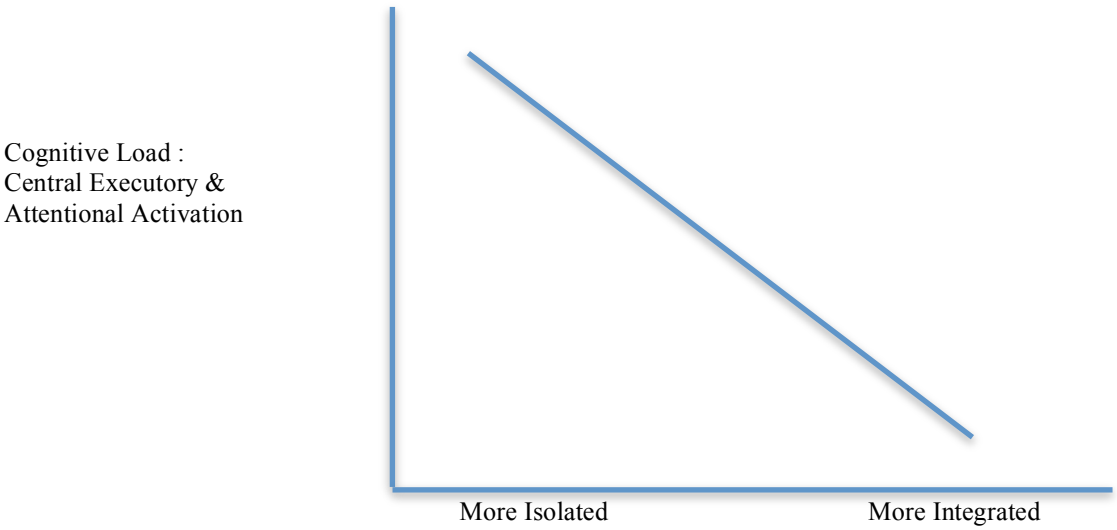


Figure 13: Attentional Activate Graph for Isolated vs. Integrated Multimedia

Application of Integrated Visualization Method to other Spatially Complex Domains:

This method of visually integrating the sub-components that comprise a domain is a generally applicable learning methodology for lower the attentional cognitive load and enhancing cohesive mental model formation for any spatially complex domain that has many sub-components that interact with each other in spatially complex ways to a high degree. This will promote better chunking and retention of both the isolated sub-components of the domain and the interconnections between sub-components. This includes but is not limited to Biology, Physics, Chemistry, Calculus Statistics, Accounting, Financial Trading Processes, Data Visualization Interfaces, Computer Science and even aspects of law, language learning and other domains. Overall, since even low spatially complex domains, like social studies, can rise to the level of high spatial complexity when enough sub-components are taught with their corresponding interactions, there is literally no system, or domain, that cannot benefit from the incisive application of this integrated visualization learning methodology.

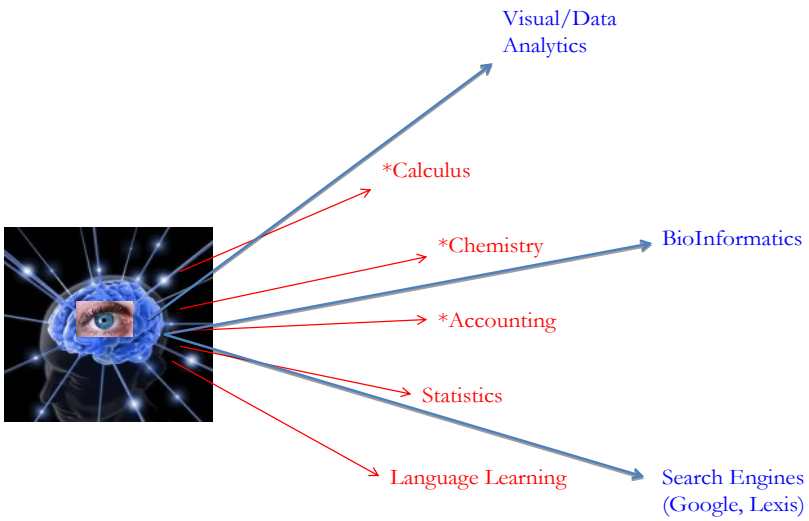


Figure 14: Domains for Integrative Visual Framework

Let's examine the electricity and magnetism unit of Physics. There are many related sub-component concepts that interact with one another, such as electrostatic Coulomb Force repulsion, voltage, potential energy, magnetic fields created by an electron, magnetic fields on a wire or electron by an external capacity, capacitance, electric fields, DC current, resistivity, power, and series and parallel circuits. It is possible to create a series of layered RC circuits, that have all of these Physics concept iteratively visualized for the students in layers, thereby greatly lowering the attentional cognitive load in long term working memory of processing the complex system of electric circuitry.

An example of how to iterative and layer three of these concepts is below. Here when the student clicks on any wire or resistor in a series or parallel circuit they see an animation depicting electrostatic repulsion between electrons which drives their voltage and current, and creates magnetic fields at every instance in a circuit. These three concepts that are related are visualized, iterated throughout the circuit, and integrated together with clickable layers.

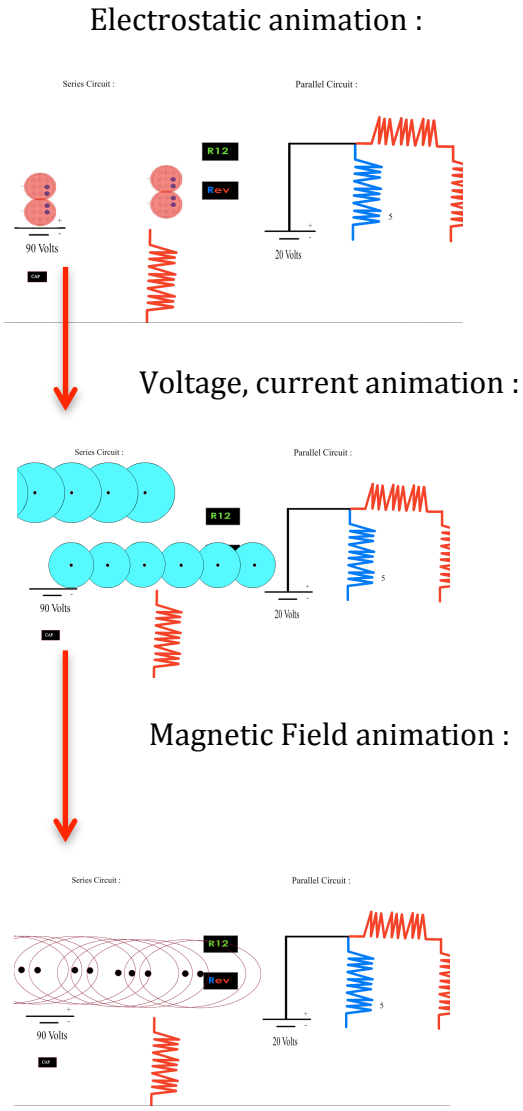


Figure 15: Layered, Integrated Visual Circuit Prototype

We can further integrate concepts from kinematics into this interactive, iterative, layered visualization by explaining and linking Newtonian mechanics concepts, such as velocity, acceleration, force, kinetic and potential energy (Voltage), momentum, collisions, inertia, rotation framed in terms of the electrons moving and repulsing each other in the circuit.

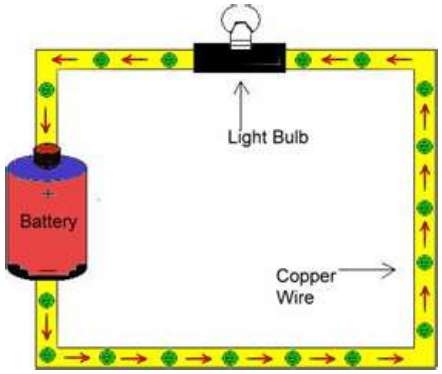


Figure 16: Circuit Visualization

Similarly, since electrons produce heat in a resistor, it is possible to visually iterate and layer thermodynamic concepts into this circuit, and light magnetic waves produce light, according to $c = f \lambda$, it is possible to connect the circuit system and integrate with wave theory and optics. Hence, the possibilities of building visually iterative and integrated external representation for physical concepts is endless and will result in *exponential* increases in learning over non-iterative, non-integrated visual external representations.

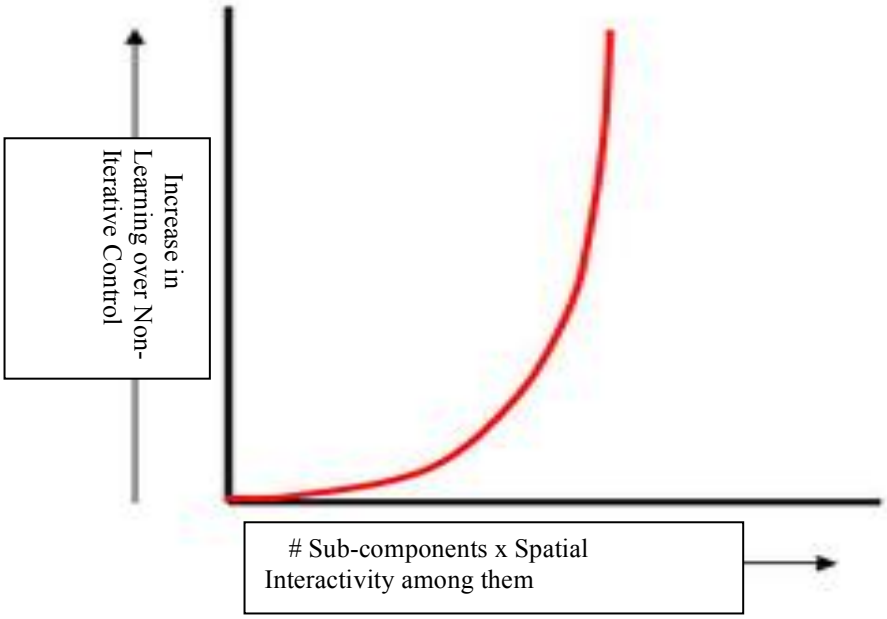


Figure 17: Graph of Spatial Complexity x Projected Learning Gains

Similarly, in chemistry that major concepts of atomic orbitals, nuclear chemistry, atomic subshells, valence interactions, and oxidation-reduction reactions all are founded on electron theory and hence can be depicted using a cohesive iterative visualization. Kinetics, acid base reactions, and phase changes are also premised upon an electron theory and hence are emergent properties of this iterative visual system for chemistry.

For Biology, the various organisms, the manner in which they interact with each other as an ecosystem, reproduce, gain nutrients from the Earth, excrete and perform life functions can be depicted as a interactive system of organisms, humans, animals and plants, where the student can click on each organism and see how it operates and interacts with other organisms at the cellular and molecular levels, akin to an extrapolation of the neural signal transmission system described in this dissertation.

Furthermore, using this Biological system, since organisms perform metabolism processes on molecules, and are subject to the laws of physics, an even higher-order iterative/integrated, integrated visual external representation of the combined complex systems of biology, chemistry and physics can be created, resulted in even greater gains in learning.

Since calculus entails learning the derivatives and integrals that underpin the areas underneath curves and the slopes that comprise graph lines, it is conceivable that discrete visual representations can be engineered to capture the spatial relationships between variables, x, y, z etc., and can be integrated using this learning system. Same goes for statistics, where they are many interrelated hypothesis tests, such as chi-square, ANOVA, log linear models which can be taught in a visually iterative and integrated fashion.

Switching to law, for an example from the humanities, corporate law, securities law and bankruptcy law and contract laws are all highly interrelated and premise upon a theory of civil procedure for litigation, and hence all of these corporate law courses can be taught much more efficiently using an iterative, integrated visual external representation.

Overarching theoretical framework: Sweller's vs. Virk LTWM Prediction for Spatially Integrated Presentation

Sweller would advocate that presenting information which elaborates beyond the core neural sub-components presented to each condition would increase the overall cognitive load of retention and recall and result in worse retention of the neural components in the integrated neural animated condition versus the isolated neural animated condition. However, under this revised Cowan Long Term Working Memory Multimedia model for visually integrative systems, the extra, detailed information which elaborates upon the interconnections among the core neural sub-components presented to each group, will increase the cognitive load of viewing the presentation for the integrated group over the isolated animations control group, but greatly decrease the internal central executive attention-modulated cognitive load of chunking the neural sub-components into a cohesive mental model along with the interconnections among the sub-components in long term working memory. Hence an integrated presentation will have an overall lower cognitive load for retention and recall.

In summary, students who are presented with non-integrated visual external representations of a *spatially* complex system, here signal transmission in the neuron, must mentally integrate, *chunk*, the various sub-parts of the spatially complex system in long term working memory, in order to create a visually integrated and cohesively *chunked* mental models of the complex system. It is duly noted, that it is assumed the humans are neurologically wired to reflexively attempt to chunk isolated information into cohesive knowledge structures.

This requires more attentional central executory cognitive resources than students have available in long term working memory, and hence cognitively overloads their working memory, resulting in the formation of incomplete mental models of the complex system, here neural signal

transmission, for sub-parts themselves and for where the sub-parts, such as the dendrite channels or phospholipids along the membrane, are *not* fully integrated. Accordingly, many spatially emergent properties of the complex system that are visible when the sub-components are fully integrated, are not activated by the student, and hence many deeply encoded spatial continuity schemas and other schemas which greatly reduce the the attentional (cognitive) load of activating and visually chunking via the central executive, the necessary representations for forming a visually integrated mental model of the complex system, here neural signal transmission, are not activated.

Thus, without activating these rich spatial schemas to scaffold the processing of the complex domain, the sum attentional cognitive load to generate a visually integrated mental model of the complex system, here neural signal transmission, is greater than the maximum attentional capacity of the student.

Conversely, providing students with visually integrated external representations, here a set of visually integrated animations of the five key phases of neural signal transmission at the cellular and molecular levels, cognitively offloads the attentional strain of mentally integrating the various sub-components of the complex domain, and all the emergent spatial properties of the system are visually manifest. Therefore many rich spatial continuity schemas, and other schemas following from this which greatly reduce the attentional load of processing and encoding the complex system are activated in the long term working memory of the student, AND the student does not need to expend great quantities of attentional resources to mentally integrate the sub-components of the system because this is already done for them. Accordingly, the sum attentional cognitive load of students viewing this visually integrated presentation of the complex domain to generate a visually integrated mental model of the complex system, here

neural signal transmission, is less than the maximum attentional capacity of the student. *This results in the student having a stronger mental model of both the neural sub-components in isolation and the interconnections between sub-components.*

Following from this theoretical framework :

Content Domain General Hypotheses :

Information elaborated by depicting interconnections among concepts with more details, a higher external cognitive load, is retained better than information that is elaborated by depicting interconnections with fewer details.

CHAPTER III

EXPERIMENT 1: PILOT STUDY

Research Questions and a priori Hypotheses

Based on the proposed cognitive model of long term memory attention activated based cognitive load, the guiding question of this first experiment is whether students shown isolated, non-integrated cellular and molecular animations and/or still images of the major steps of signal transmission in the neuron along with the general locations of the major neural structures on a wireframe neuron and less detailed descriptions of the interconnections among the steps can generate a mental model of the neural sub-components presented equivalent to students shown a cellular and molecular animations of the major steps of signal transmission in the neuron which has all of the neural sub-components integrated and layered into a detailed whole?

H. Students shown detailed integrated, layered cellular and molecular level animated videos of the major neural subcomponents in the neuron will perform significantly better on free response questions than students shown less detailed, isolated videos.

Specifically, here both the integrated and isolated groups view stop frame style animated videos and both groups view wireframe diagrams of the neuron. The integrated group receives detailed descriptions of the interconnections among subcomponents while the isolated group receives less detailed descriptions.

Participants

Participants were 32 Teacher's College graduate students (N=14, control; N=18, experimental) recruited from Teacher's College Graduate Online Courses in Cognition and Learning and Psychology of Thinking assigned to treatments. Participation was a mandatory requirement for course credit, and all students signed online consent forms in order to participate.

Design

The design of the study is a between-subjects quasi-experimental design. Half the students in a class alphabetically were randomly assigned to one of the two conditions respectively. They were informed that as per their course research participation requirements, they must complete this experiment in a single sitting, within one week of being notified via e-mail of the assignment. All students were be informed they will be learning a biological science topic and for up to 30 minutes, at the end of which they would answer a set of questions to assess what they had learned from the materials, and would be debriefed in the following week.

Materials and Apparatus

The content used in the control condition isolated flash animations and corresponding auditory accompaniment which was to mirror "traditional" neuroscience instruction and model that way in which often key interrelationships between neuron subcomponents are explained using less detailed terms. As a result often key states in signal transmission are never explained explicitly in any form. The content was modeled after the description of neural signal transmission in pages 282-290 of the *MCAT Biology Review : Comprehensive review, practice and strategies* (2010). Content for the molecular videos and transcripts were taken from prominent online and textbooks molecular biology resources, and reviewed by a neurobiology expert.

The content used in the experimental condition integrated flash animations was created by integrating the visualizations for the core neural cellular and molecular subcomponents in Flash CS3/5.5 and then coming up with an auditory accompaniment that corresponded to this visualization. The information used was largely derived from the author's extensive experience

with neuroscience and biochemistry having double majored in neuroscience and neurobiology and various online neuroscience websites.

Each of the videos for the control condition were assembled into a website, created using Dreamweaver CS3, and each of the videos for the experimental group were also assembled into a website. Web links to the consent form, an introductory video that overviewed how to navigate the website, and a link to the assessment questions for each condition were also added to both websites. The apparatus varies from student to student, as they view their experimental website using a computer of their choosing. The websites were hosted using hostmonster.com.

Experimental Conditions

**Pleases see Appendices A, C for verbal transcripts for conditions*

The control condition (N=14), 12 minutes long, consisted of first a short video explaining the basic overall wireframe structure of the neuron (please see Figure 1) and then isolated flash animations with audio explanations of the five stages of signal transmission in the neuron. But here the various components that make up the neuron in a cellular view, are not integrated throughout the visualization, but rather shown in isolation (please see Figure 2). There were four animations total, as the fifth step of signal transmission was not animated but described verbally.

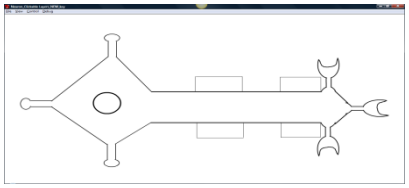


Figure 18: Control Condition Screenshot of Wireframe Neuron Video

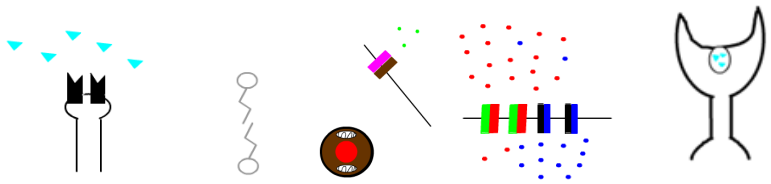


Figure 19: Control Condition Screenshots of Isolated Cellular Animations

After viewing these cellular animated videos (please see Appendix E for almost identical screenshots from experiment 2), subjects then viewed a video describing static pictures of the molecular structures that comprise these cellular structures (Figure 3). Please note a text and diagrams only lesson of this lesson was created as a secondary condition and run on 12 subjects, which was thrown out of this initial analysis.

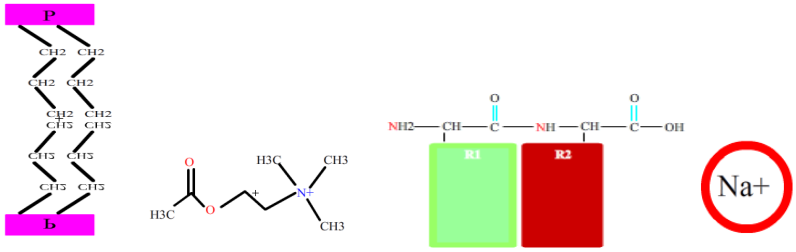


Figure 20 : Control Condition Screenshots of Molecular Structures Video

The experimental group (N=18), 28 minutes long, the integrated visual external representation group, consisted of the same wireframe video as the control and flash animations for the same five steps of signal transmission, here step 4 has an entire video. However, now the animation shows students what the same steps look like when all the sub-parts of the neuron are "integrated" throughout the visualization, so everything is completely integrated. For example, the phospholipid structure is integrated, or appears, every time it should along the wireframe

membrane of the neuron, as does the dendrites, sodium and potassium channels, and all other component structures of the neuron (please see Figures 21-23 for diagrams of examples of this integration process, and Appendix G for almost identical screenshots from experiment 2).

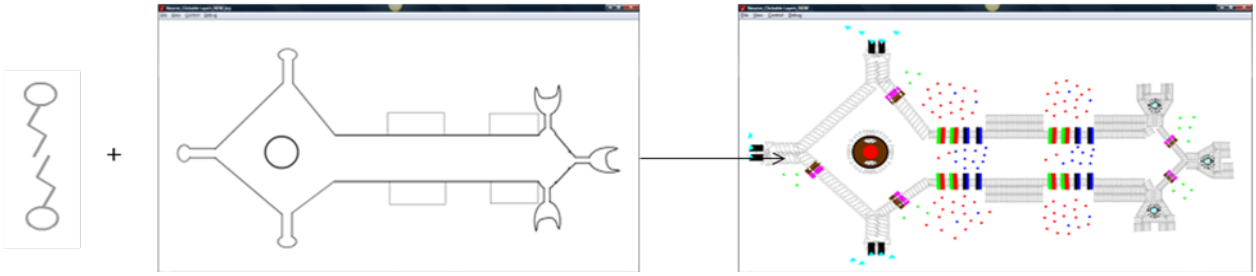


Figure 21: "Integrating" the phospholipid throughout the integrated visual neuron model along every neuron membrane

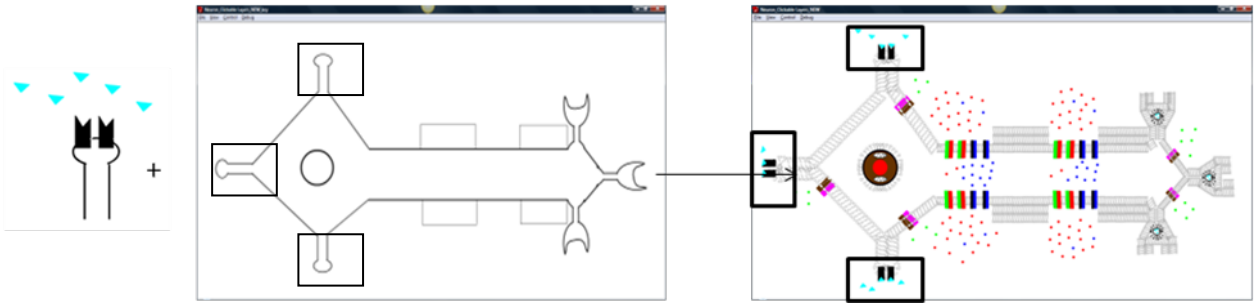


Figure 22: "Integrating" the dendrite throughout the integrated visual neuron model, so it appears every time it should occur

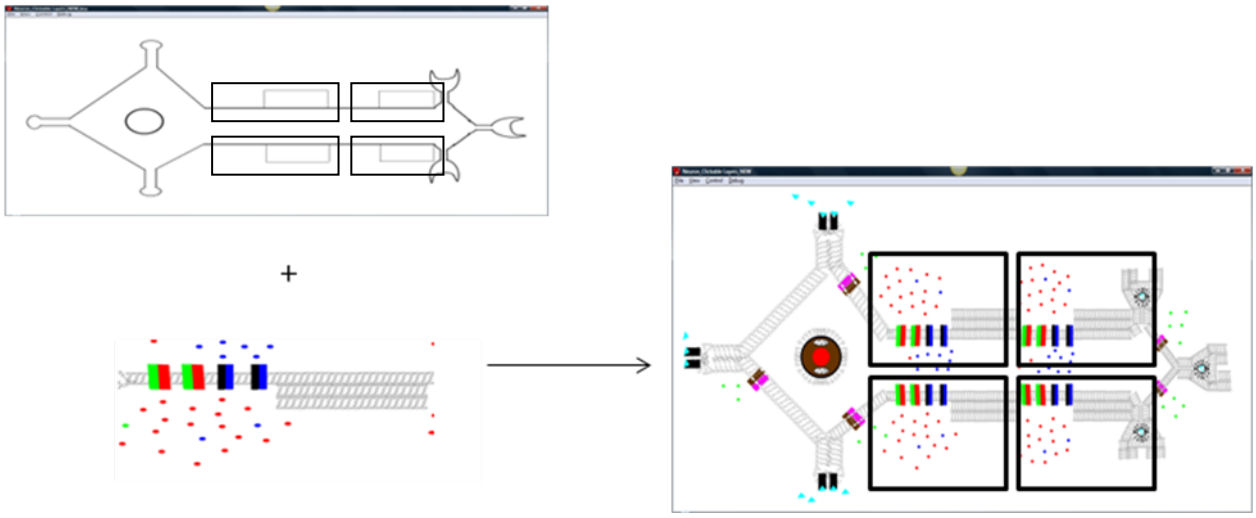


Figure 23: "Integrating" the action potential channels and myelin sheaths throughout the integrated visual neuron model so they occur at every instance along the axon at the top and bottom

Additionally, students were shown molecular animated videos of the same five steps of signal transmission, but here the molecular structures were integrated throughout the wireframe model as with the cellular videos (figure 7, and Appendix C). Due to resolution problems, the students only saw the relevant portions of the integrated molecular videos for each step, instead of viewing the entire molecular for the entire neuron for every video, as with the cellular videos. Students were shown a screenshot of the relevant cellular structures for each step before seeing the corresponding molecular video, in this way, the integrated condition has the cellular and molecular levels layered one atop another (figure 8).

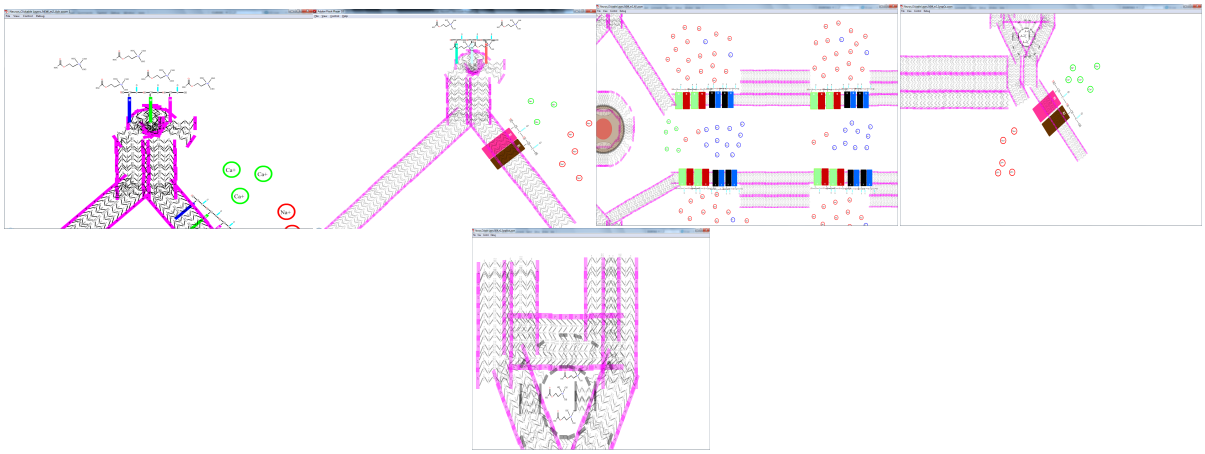


Figure 24: Integrated Visualization Condition, Molecular Signal Transmission Steps Videos Screenshots

Figure 25: Student sees screenshot of cellular level of dendrite before seeing molecular video for this step of signal transmission, an example of how the integrated visualization is "layered"

Independent Variables

The type of neuroscience cellular, or molecular stop frame animation/still frame instructional videos presented, isolated (control) or integrated (experimental) was the independent variable.

Dependent Variables

A. Spatial Ability and Prior Neuroscience Coursework/Scoring

All students were given the Vandenberg and Kuse Mental Rotation task as a test of their spatial ability, to be used as a covariate, but since the students did not split evenly into high and low spatial groups this test had to be thrown out of the analysis. Also, students were surveyed on their prior neuroscience coursework and divided into high and low neuroscience background groups, according to whether they had taken neurosciences courses prior to the experiment or not. No significant differences based on prior neuroscience coursework were found.

B. There are three measures of learning which comprise the assessment :

These measures are scored according to various rubrics, where details and concepts receive a point value from .25 to 2, depending on the importance of the detail. Please see the detailed rubrics in the **Appendix D for detailed information about how each sub-section here is scored.*

1. Free response essay questions, one which instructs the student to explain the steps of signal transmission in the neuron drawing based upon the instructional materials and also any steps not described in the instructional materials that are logically necessary for the process to work and make sense. Please see Appendix D, for text of essay prompt.

Scoring:

Students essays were scored (Appendix D) on three sub-scales, a free response essay total

score for the overall essay, a free response essay cellular terminology subscore, and free response essay molecular terminology subscore. The cellular and molecular terminology subscores detected only information in the student essay response which used cellular and molecular terminology used in the instructional videos and centered on concepts that were explicitly presented visually and verbally in the experimental, integrated condition only, while the total score accounted for all information presented and overlaps with both of these subscores.

2. Individual expository free response short answer questions about signal transmission concepts that were visual and verbally explicit in the integrated signal transmission animations (experimental condition), but students shown the isolated signal transmission animations (control) would have to chunk by mentally integrating the neuronal components they were shown. Please see Appendix D, for examples.

Scoring:

Scoring for the expository free response questions, follows the same procedure as the essay, students are given credit for information in their response which included cellular and molecular terminology which tended to deal with concepts explicit only in the integrated condition, the individual free response cellular and molecular terminology subscores respectively, and their overall score for the cellular and molecular questions.

3. Individual free response short answer "What If" questions where students have to engage in thought experiments and manipulate their signal transmission mental models in order to predict the outcomes of scenarios where the values of key *cellular* and *molecular* entities comprising the neuron (such as the number calcium channels,

amount of myelin, number of subunits) are altered. Please see Appendix D, for examples.

Scoring

Similar to the free response expository section, students are given credit for information in their response which included cellular and molecular terminology which tended to deal with concepts explicit only in the integrated condition, the individual free response What-If cellular and molecular terminology subscores respectively, and their overall score for the cellular and molecular questions.

Procedure

Teacher's College Graduate Students in Online Course were assigned to either the control or experimental condition, according to whether they were in the first or bottom half of the class alphabetically and were e-mailed instructions about how to access the corresponding experimental website and the due date and submission requirements for the experiment. Their participation in the experiment was part of their mandatory online research participation requirements which is stated in their course syllabi. Students were instructed to complete the experiment in one sitting in a quiet place with minimal to no distractions. They went go to their assigned experimental website, fill out the consent form available on the website, watched the videos and then downloaded the assessment. Students then completed the assessment on their respective computers, using MS Word, and e-mailed the assessment and consent form to my gmail.com e-mail address (cogsci7@gmail.com). Shortly after all students have submitted their assessments and consent forms, a debriefing form was be e-mailed to all students.

Results

No significant differences based on prior neuroscience ability were found. Each category of assessment question and its subscore was treated as a dependent variable and accordingly, one way ANOVA's were conducted on each of the dependent variables displayed after each of three data tables encompassing the three major question types:

Please note the following conventions for the data tables herein:

* = $p < .05$
** = $.05 > p > .01$
*** = $p < .01$

Table 1: Free Recall Essay

Condition	FREtotal	***FRECell	FREMol
Isolated Visuals	M = 14.93/119 SD = 5.53	M = .32/21 SD = .54	M = .36/22 SD = .84
Integrated Visuals	M = 17.94/119 SD = 10.48	M = 2.58/21 SD = 2.23	M = .58/22 SD = 1.33
	F = .948 df = 31 p >.05	F = 13.669 df = 31 p< .005 Coh. D = 1.36	F = .307 df = 31 p > .05

Note: Means are presented in the format "Mean Score for DV"/"Total Possible Points for DV"

FREtotal: Total Free Response Essay Score

FRECell: Free Response Essay Cellular Terminology SubScore

FREMol: Free Response Essay Molecular Terminology SubScore

Table 2: Individual Free Recall Essay Short Answer Scores

Condition	***IndFRCellTotal	***IndFRCellTerm	IndFRMolTotal	IndFRMolTerm
Isolated Visuals	M = 6.95/40.5 SD = 4.77	M = 1.23/27 SD = 1.58	M = 7.68/88 SD = 6.12	M = 6.04/81 SD = 5.58
Integrated Visuals	M = 14.06/40.5 SD = 7.49	M = 7.31/27 SD = 4.78	M = 12.36/88 SD = 8.35	M = 6.92/81 SD = 5.35
	F = 9.55 df = 31 p < .005 Coh. D = 1.14	F = 20.67 df = 31 p< .005 Coh. D = 1.68	F = 3.10 df = 31 p = .089 Coh. D = .65	F = .206 df = 31 p > .05

Note: Means are presented in the format "Mean Score for DV"/"Total Possible Points for DV"

IndFRCellTotal : Individual Free Response Cellular Questions Total Score

IndFRCellTerm. : Individual Free Response Cellular Questions Terminology SubScore

IndFRMolTotal : Individual Free Response Molecular Questions Total Score

IndFRMolTerm.: Individual Free Response Molecular Questions Terminology SubScore

Table 3 : Individual Free Recall What-If Question Scores

Condition	*IndFRWF CellTotal	***IndFRWF CellTerm	IndFRWF MolTotal	IndFRWF MolTerm
Isolated Visuals	M = 2.82/34 SD = 1.77	M = .21/19 SD = .43	M = 1.79/40 SD = 2.15	M = .36/8.5 SD = .74
Integrated Visuals	M = 4.75/34 SD = 2.90	M = 2.11/19 SD = 1.74	M = 3.64/40 SD = 3.98	M = .69/8.5 SD = 1.56
	F = 4.78 df = 31 p < .05 Coh. D = .81	F = 15.85 df = 31 p< .005 Coh. D =.79	F = 2.46 df = 31 p > .05 Coh. D =.77	F = .55 df = 31 p > .05

Note: Means are presented in the format "Mean Score for DV"/"Total Possible Points for DV"

IndFRWFCellTotal : Individual Free Response Cellular "What If" Questions Total Score

IndFRWFCellTerm : Individual Free Response Cellular "What If" Questions Terminology SubScore

IndFRWFMolTotal : Individual Free Response Molecular "What If" Questions Total Score

IndFRWFMolTerm : Individual Free Response Molecular “What If” Questions Molecular Terminology SubScore

A one-way ANOVA demonstrated there were highly significant differences among the groups $F(1,31) = 13.67$, $MSE = 40.29$, $p < .005$ for the free response essay cellular terminology subscore. The integrated group ($M = 2.58$, $SD = 2.23$) performed significantly better than the isolated group ($M = .32$, $SD = .54$) for this subsection.

A one-way ANOVA demonstrated there were highly significant differences among the groups $F(1,31) = 9.55$, $MSE = 398.00$, $p < .005$ for the individual free response cellular questions total score. The integrated group ($M = 14.06$, $SD = 7.49$) performed significantly better than the isolated group ($M = 6.95$, $SD = 4.77$) for this subsection.

A one-way ANOVA demonstrated there were highly significant differences among the groups $F(1,31) = 20.67$, $MSE = 290.48$, $p < .001$ for the individual free response cellular questions cellular terminology subscore. The integrated group ($M = 7.31$, $SD = 4.78$) performed significantly better than the isolated group ($M = 1.23$, $SD = 1.58$) for this subsection.

A one-way ANOVA demonstrated there were marginally significant differences among the groups $F(1,31) = 4.78$, $MSE = 29.29$, $p < .05$ for the individual free response cellular “what if” questions total score. The integrated group ($M = 4.75$, $SD = 2.90$) performed significantly better than the isolated group ($M = 2.82$, $SD = 1.77$) for this subsection.

A one-way ANOVA demonstrated there were significant differences among the groups $F(1,31) = 15.85$, $MSE = 28.33$, $p < .001$ for the individual free response cellular “what if” questions cellular terminology subscore. The integrated group ($M = 2.11$, $SD = 1.74$) performed significantly better than the isolated group ($M = .21$, $SD = .43$) for this subsection.

A one-way ANOVA demonstrated there were no significant differences among the groups on the free response total, free response molecular terminology subscore, individual free response short answer molecular total and terminology score/subscore, "What If" molecular total score or the corresponding molecular terminology subscore. However, the individual molecular free response short answer total score had a mild trend toward significance, with a p-value of .089.

Discussion

Students in the integrated, layered visualization condition performed significantly better than the control condition on all of the individual cellular free response questions and respective subscores and on the free response essay cellular terminology subscores. This supports the hypothesis that the visuo-spatial attentional cognitive load of integrating the various images/concepts in long term working memory in the control condition for the cellular concepts is greater than what most students are capable of. Hence there are many signal transmission concepts at the cellular level that control students are incapable of chunking, "gaps" that need to be explicitly depicted using integrated neuroscience visualizations. However, while there was a slight trend on some of the molecular questions there were no significant differences between groups on the molecular individual free response questions or the free response essay molecular subscore, which argues against the hypothesis, esp. the idea that layering various levels of information is important to understanding complex scientific systems. Overall, there is still strong evidence for the hypothesis that at least with the cellular models for the neuron, integrated visualizations are very important to make sure students understand signal transmission in the neuron completely without any gaps in their mental model.

The argument could be raised that any significant increase in performance in the experimental visualization conditions may simply be due to the extra time students spent learning the material, and not the integrated, layered visualizations. This assertion will be controlled for in the dissertation study, experiment 2, where time on task will be equivalent for both conditions along with greater focus on presenting the locations of the subcomponents on the wireframe and analyzing cellular information presented equivalently to both groups. The molecular information, and exploring the process of layering information linked at different levels is not included in the dissertation study.

CHAPTER IV

EXPERIMENT 2: DISSERTATION STUDY

Based on the proposed cognitive model of long term memory attention activated based cognitive load, the guiding question of this experiment is whether students shown isolated, non-integrated cellular animations of the major steps of signal transmission in the neuron along with the locations of the subcomponents on a wireframe neuron and less detailed descriptions of the interconnections among the steps can generate a mental model of the neural sub-components presented equivalent to students shown a cellular animation of the major steps of signal transmission in the neuron which has all of the neural sub-components integrated into a detailed whole? Accordingly the following a priori hypothesis follows based on this cognitive model:

Major hypothesis for Neural Signal Transmission Complex Domain :

H. Students shown detailed, integrated cellular animated videos of the major subcomponents in the neuron will perform significantly better on free response questions and diagram questions than students shown less detailed, isolated videos.

Specifically, here both the integrated and isolated groups view stop frame animated videos. Both groups will view wireframe diagrams of the neuron, but only the isolated group will have the locations of these subcomponents pointed out repeatedly on the wireframe throughout treatment before they view the corresponding animations.

Participants

The participants are 32 Teacher's College Graduate Students in Online Course Sections (N= 17, control ; N = 15, experimental). Participation was a mandatory requirement for course credit, and all students signed online consent forms in order to participate.

Design

The design of the study is a between-subjects experimental design. Students were randomly assigned to one of the two conditions. They were informed that as per their course research participation requirements, they must complete this experiment in a single sitting, within one week of being notified via e-mail of the assignment. All students were be informed they will be learning a biological science topic and using some instructional materials for approximately 10 minutes, at the end of which they would answer a set of questions to assess what they had learned from the materials, and would be debriefed in the following week.

Materials and Apparatus

Overview of material used to create conditions and overall experimental design

The content used in the control condition isolated flash animations and corresponding auditory accompaniment which was to mirror "traditional" neuroscience instruction and model that way in which often key interrelationships between neuron subcomponents are explained using less detailed terms, and as a result often key states in signal transmission are never explained explicitly in any form, was modeled after the description of neural signal transmission in pages 282-290 of the *MCAT Biology Review : Comprehensive review, practice and strategies* (2010).

The content used in the experimental condition integrated flash animations was created by integrating the visualizations for the core neural cellular subcomponents in Flash CS3/5.5 and then coming up with an auditory accompaniment that corresponded to this visualization. The information used was largely derived from the author's extensive experience with neuroscience and biochemistry having double majored in neuroscience and neurobiology and various online neuroscience websites.

All flash animations for the cellular animations for both the control and experimental groups were created using Flash CS3 and all of the molecular animations were created using

Flash CS 5.5 (for technical reasons). In order to add audio to the flash animations Camtasia Studio 6 audio recordings were made of myself going thru the animations and orating the auditory accompaniment. This process was easier than adding audio to Flash directly due to technical issues. The assessment questions and consent form was created using MS Word, including the diagram-labeling questions.

Each of the videos for the control condition were assembled into a website, created using Dreamweaver CS3, and each of the videos for the experimental group were also assembled into a website. Web links to the consent form, an introductory video that overviewed how to navigate the website, a video explaining how to use the drawing toolbar of MS Word to answer any diagram labeling questions on the assessment and a link to the assessment questions for each condition were also added to both websites. The apparatus varies from student to student, as they view their experimental website using a computer of their choosing. The websites were hosted using hostmonster.com.

Detailed Examination of Experimental Conditions :

Control : Isolated Visuals

The control condition, approximately 10 minutes long, is summarized below, with key screenshots taken from each of the animated videos below. Please note, that as with the experimental group, the animations used did not depict continuous, dynamic motion, rather they were a series of key states, such as the key states of a neurotransmitter moving towards and binding to a dendrite, weaved together, "stop frame" animation. The introduction to this condition is approximately 1 minute, the signal transmission lesson is 6 minutes approximately, and a short review of the material after the lesson is approximately 3 minutes long. Please see Appendices A and B, for a more detailed set of screenshots and the verbal transcript explanations for this condition and visit the website below to see the control condition first hand :

www.neuronc.lawschoolaids.com (control)

I. First, key structures on the neuron were pointed out on the wireframe along with small images representing these structures (dendrites, phospholipids, calcium channels etc.) as an introduction to the lesson. This introduction was matched in content to the introduction for the experimental condition.

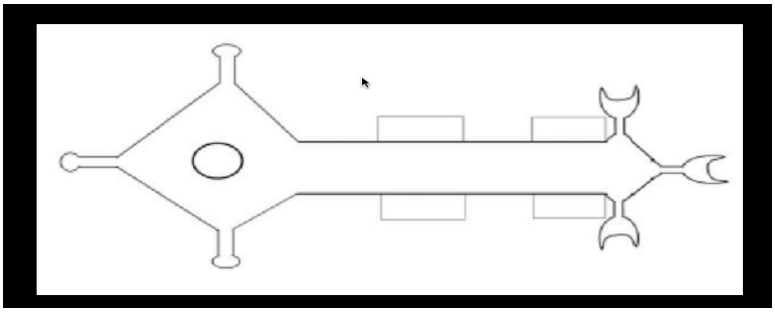


Figure 26: Wireframe from Neuron Introduction

1. Next, the location of the phospholipid on the wireframe and structure explained :

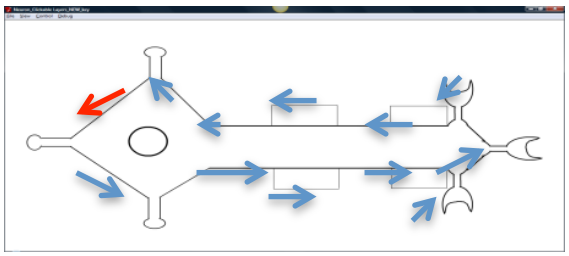


Figure 27: Cursor follows along membrane edge where arrows are to show location of phospholipids

Figure 28: Explanation of phospholipid as a unit of the membrane

2. The three locations where dendrites are found are pointed out on the wireframe model below :

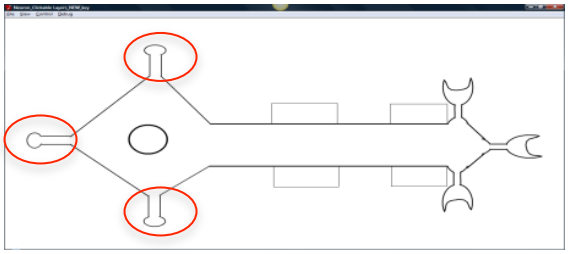


Figure 29: Locations of dendrite on wireframe

Then an animation of the neurotransmitter binding to the dendrite is shown :

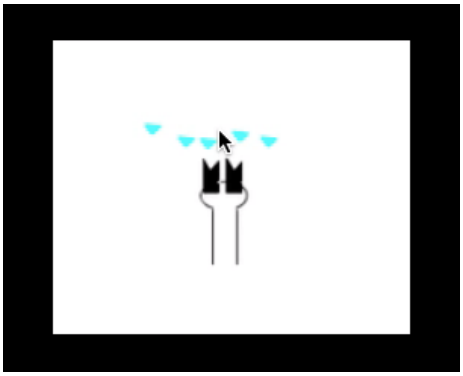


Figure 30: Animation Screenshot of dendrite binding to neuron

3.The five locations where calcium channels and ions are found are pointed out on the wireframe model below :

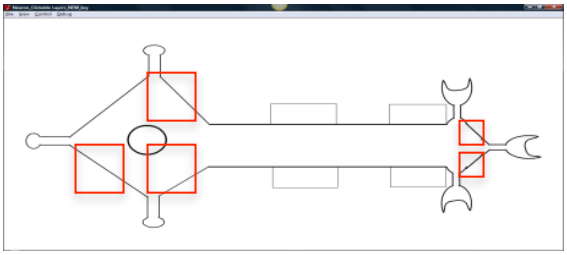


Figure 31: Calcium channel locations on wireframe

An animation of calcium channel opening and Calcium ion flow thru Channel Explanation and Animation is shown :

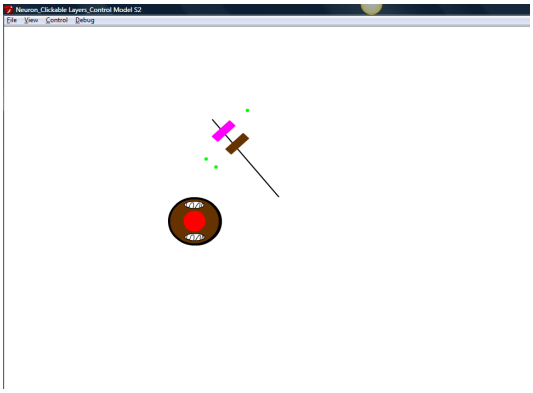


Figure 32: Calcium Channel Screenshot

4. The four locations where Sodium and Potassium Channel Action Potential Channels are found are pointed out on the wireframe model below :

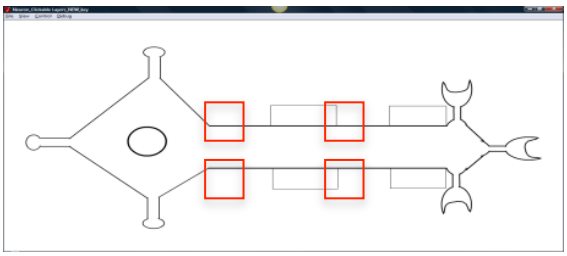


Figure 33: Locations of AP Channels on wireframe

Then an animation of Sodium influx and Potassium Efflux are shown:

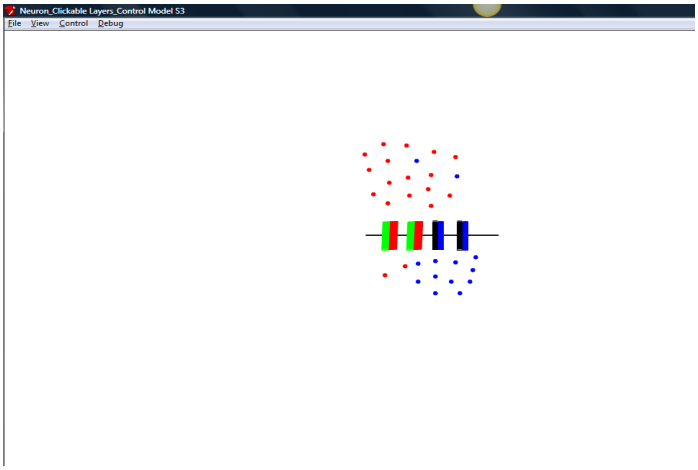


Figure 34: AP Channels

5. The three locations where the synaptic boutons are found are pointed out on the wireframe model below :

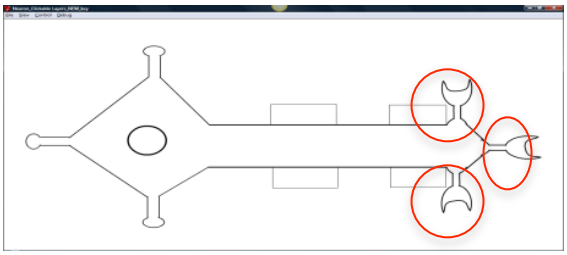


Figure 35: Synaptic Boutons on Wireframe

Then an animation of the vesicle binding to the synapse and neurotransmitter release is shown:

Figure 36: Neurotransmitter Release Screenshot

R. A 3 minute review of all these signal transmission steps is shown, to match the length of time students spend on control and experimental (10 minutes each).

Experimental Group : Sub-parts integrated Visuals

The experimental group, also approximately 10 minutes long, the integrated visual external representation group, consisted of the similar wireframe introductory video as the control and stop frame animated videos for the steps of signal transmission. Please see *Appendix G and H* for a detailed set of screenshots with verbal transcript text explanation outlining all the major sections of this condition and visit the website below to explore this condition first hand :

www.neurone.lawschoolaids.com

However, now the animation shows students what the same steps look like when all the sub-parts of the neuron are visually duplicated throughout the visualization, so everything is completely integrated into the wireframe. For example, the phospholipid structure is duplicated, every time it should along the wireframe membrane of the neuron, as does the dendrites, sodium and potassium channels, and all other component structures of the neuron. As with the control animated videos, all of these animated videos had auditory accompaniment which explained the visuals.

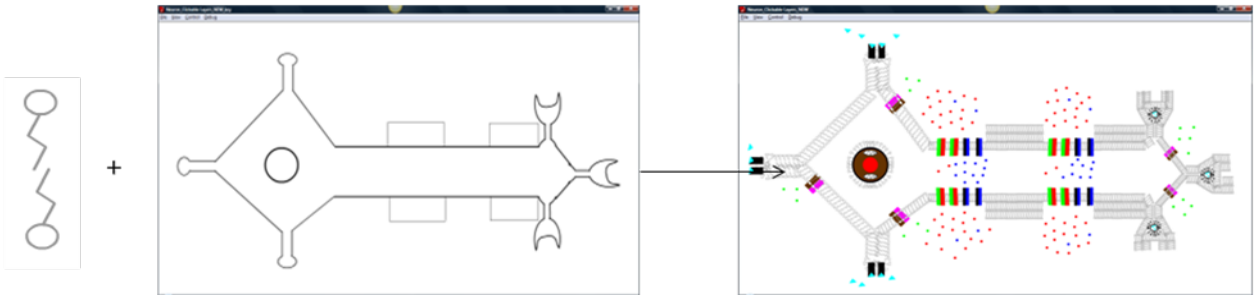


Figure 37: Integrating the phospholipid throughout the integrated visual neuron model along every neuron membrane

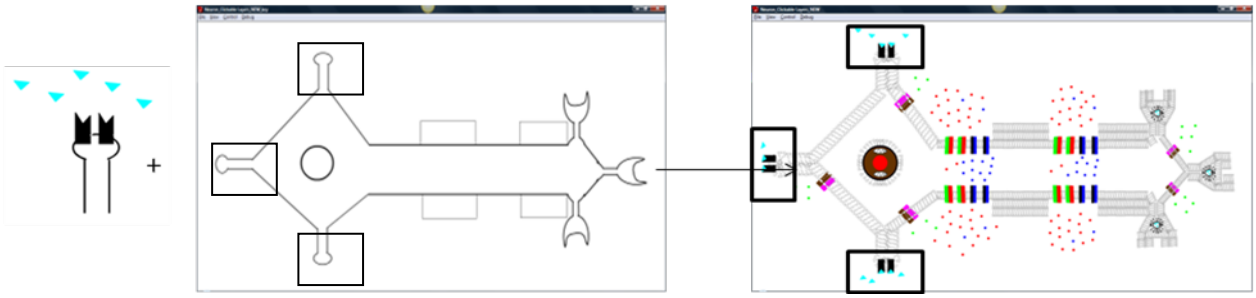


Figure 38: Integrating the dendrite throughout the integrated visual neuron model, so it appears every time it should occur

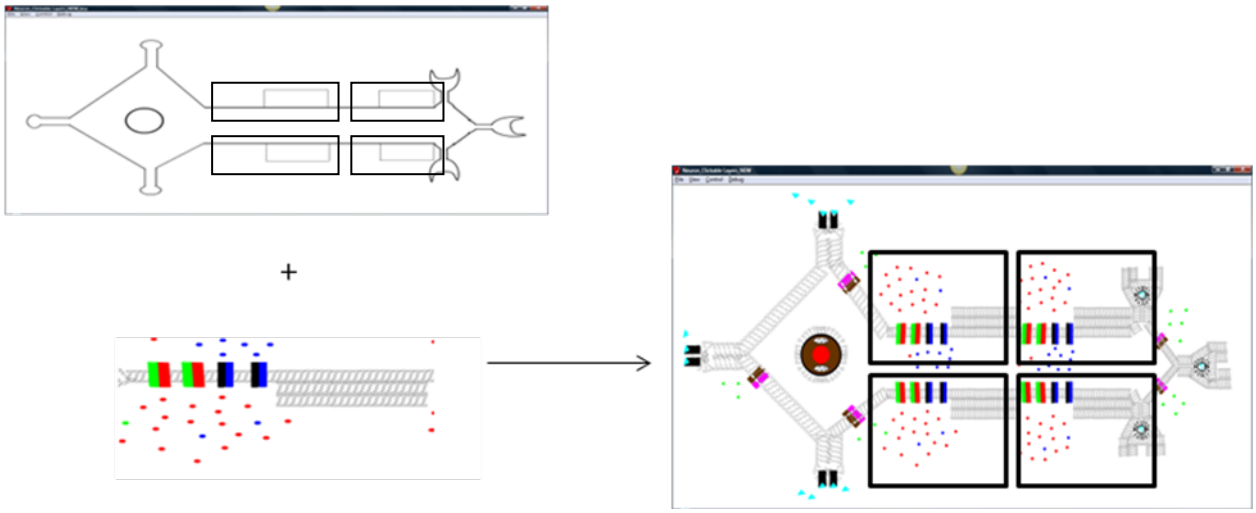


Figure 39: Integrating the action potential channels and myelin sheaths throughout the integrated visual neuron model so they occur at every instance along the axon at the top and bottom

Experimental Condition : Screenshots of major steps

**Please see Appendix G, and visit the website for detailed screenshots*

**Please see Appendix G for Introduction Screen captures*

STEP 1 : Experimental : Cellular : : Neurotransmitter (Ach) binding to Dendrite receptor

Phospholipid structure zoomed in on, and explained in context of entire animation:

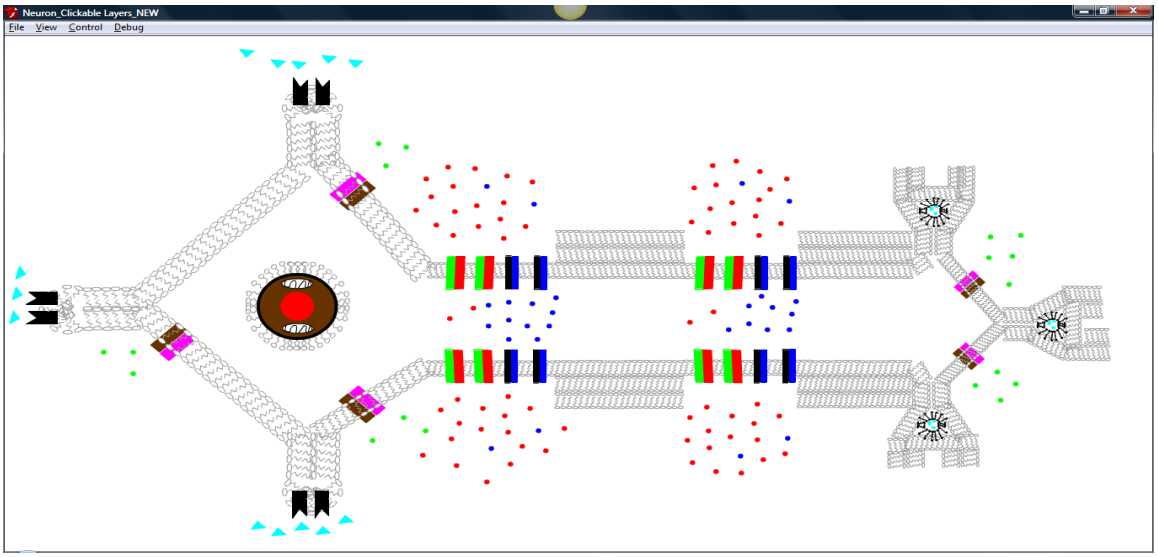


Figure 40: Screenshot of Integrated Neuron with Phospholipid

STEP 2 : Experimental : Cellular: Calcium Channel @ Soma opening

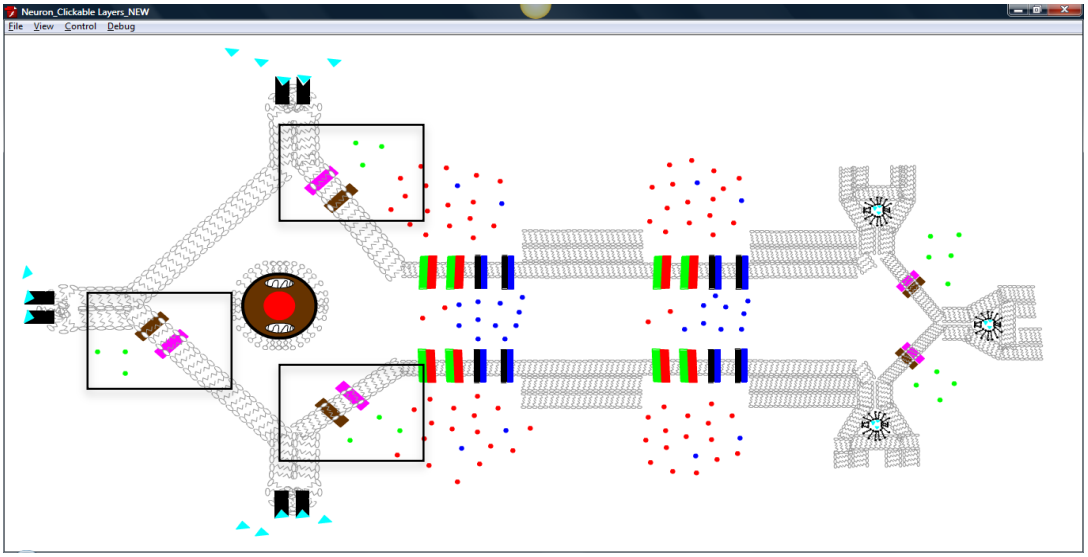


Figure 41: Screenshot of Integrated Neuron w/Calcium channels boxed

STEP 3 : Experimental : Cellular: Action Potential Propagation

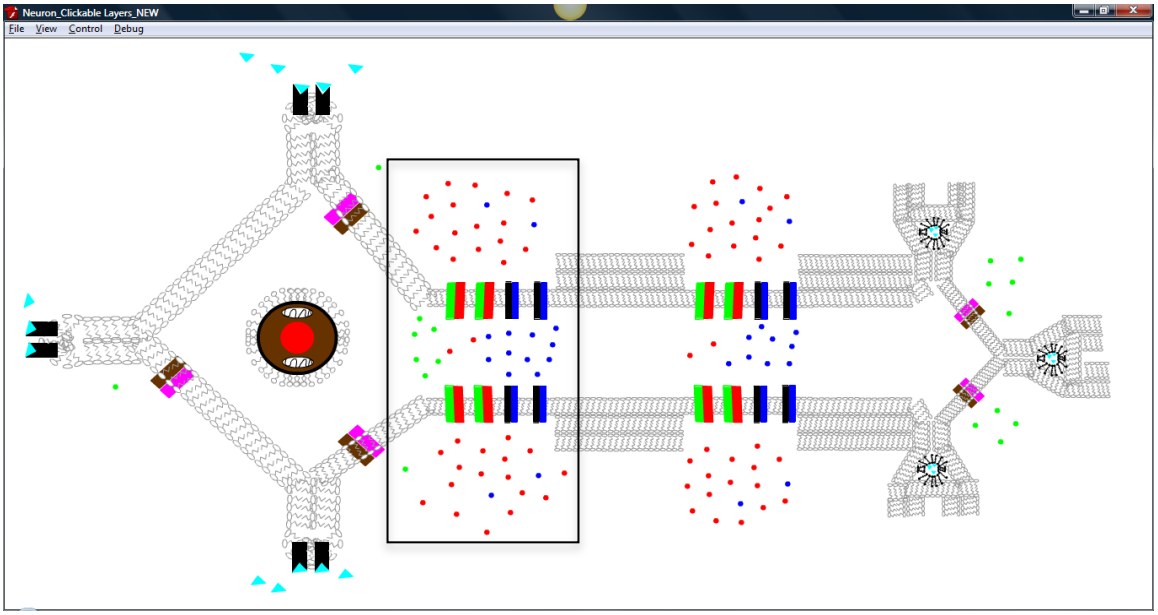


Figure 42: Screenshot of Integrated Neuron w/Initial AP channels boxed

STEP 4 : Experimental : Cellular : Calcium Channel @ Synaptic Bouton Opening

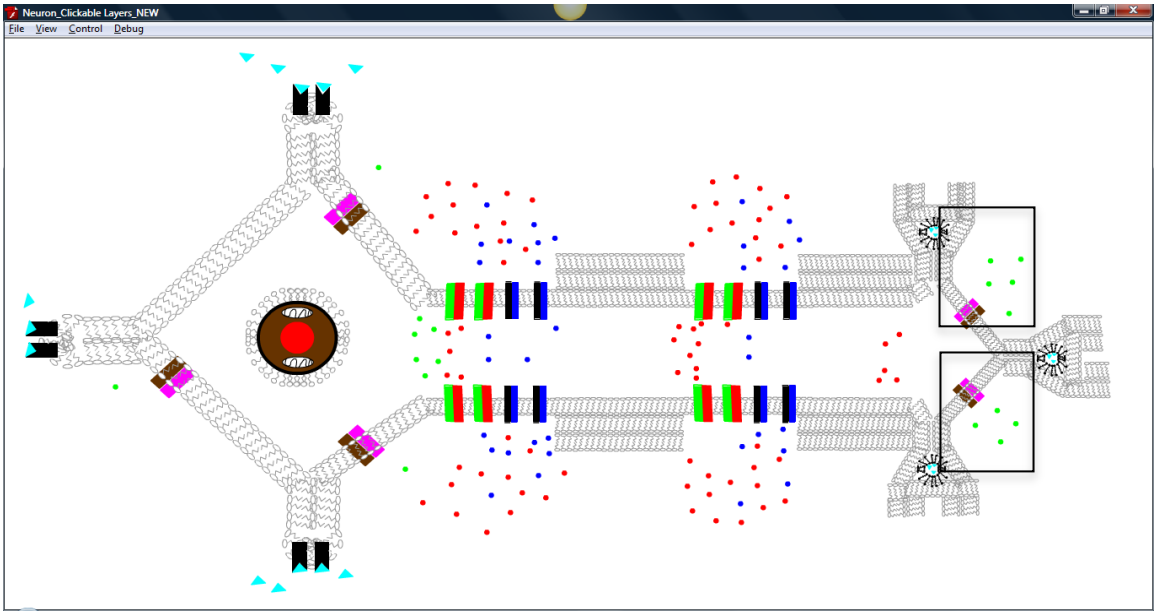


Figure 43: Screenshot of Integrated Neuron w/Synaptic Ca+ channels boxed

STEP 5 : Experimental : Cellular : Synaptic vesicle merger and release

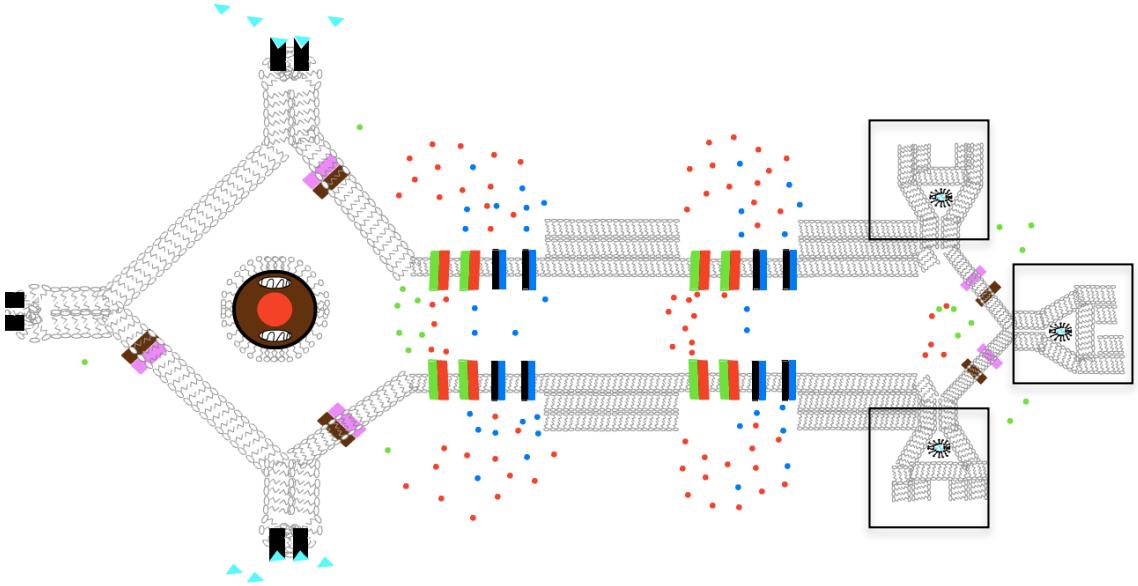


Figure 44: Screenshot of Integrated Neuron w/Synaptic Boutons boxed

Key Neuron Sub-Component Interconnections in the Context of the Action Potential Lesson

There are 8 key detailed interconnections in the neural signal transmission lesson, that were depicted visually explicitly in the integrated visualization but not the control condition:

CELLULAR DETAILED INTERCONNECTIONS OVERVIEW :

- Interconnection 1 : Calcium triggers Sodium Channels to open and start AP
- Interconnection 2 : Sodium from first AP dissipate and trigger voltage-gated sodium channels of the second action potential to open and cause the 2nd action potential
    - Sub-sub-score : *Explicit re-enumeration of second Action Potential event in axon*
- Interconnection 3 : Myelin Sheath insulates sodium ions from leaking and is comprised of layers of phospholipids <may be explained thru Detailed Interconnection 4 description>
- Interconnection 4 : The sodium ions which inflow from the second set of action potential channels dissipate along the dense layers of phospholipids which insulate them from leaking en route to Ca+ channels (path must be delineated here)
- Interconnection 5 : Na+ triggers Calcium channels to open (trigger, no path denoted)
- Interconnection 6 : Synaptic vesicles are made of phospholipids which insulate the neurotransmitters from leaking
- Interconnection 7 : Synaptic vesicle merges phospholipids with Synaptic Bouton phospholipids during release

- Interconnection 8 : Cluster of positive Ca+ ions inflowing from synaptic bouton calcium channels cause the synaptic-vesicle-synaptic bouton merger

Some of these interconnections have less detailed verbal versions in the control condition. For example, a key cellular-level less detailed interconnection is that "Calcium triggers Sodium Channels to open and start Action Potential". Another key cellular level less detailed interconnection is that "Sodium from first AP dissipate and trigger voltage-gated sodium channels of the second action potential to open, and the sodium ions of the second action potential dissipate and trigger the voltage-gated Na+ channels of the third channel, and so forth…."

Information presented equivalently to each condition, "Neuron Sub-Components":

7 concepts that are explicit in both conditions, equivalently, about the key neuron sub-components, below (also in *Appendix I*) :

1. Phospholipids run along membrane/within boxed my. Sheath areas
2. Phosphates made of hydro/carbons
3. Neurotransmitter Binds to dendrite
4. Calcium channels open and calcium ions flow
5. Action Potential
6. Synaptic bouton merger
7. Recursive Nature of Signal transmission

Overall, the isolated group has the neuron sub-components verbally elaborated through less detailed verbal description of interconnections, and explicit verbal/visual repetition of the information in the presentation, while the integrated condition elaborates neuron sub-component information through explicit visual animations and verbal descriptions of the interconnections between sub-components. Specifically, let's compare in detail what was presented for two concepts, 1. The calcium channels opening and closing, and 2. The AP Channels opening and closing.

Case Study : *Calcium Channel Opening/Closing Concept*

Comparison of what information was presented to both groups for the Calcium channel concept, entails breaking down what was presented visually and verbally, as in the chart below:

Table 4: Compare/Contrast Ca+ Channel Concept for Conditions:

	Isolated Representation	Integrated Representation
Verbal		
-Open, closing of channel	YES-SAME	YES-SAME
-Location of Top Ca+ channel	Mentioned in introduction Mentioned in lesson w/wireframe	Mentioned in introduction Mentioned briefly in lesson
-Repetition of verbal information	YES, video recap	YES, when detailed interconnection step explored
Visual		
-Open, closing of channel	YES, but no phospholipid bckgrnd.	YES, and phospholipid bckgrnd.
-Location of Top Ca+ channel	*Pointed out on wireframe in introduction and in lesson	Pointed out during introduction on wireframe and lesson on integrated neuron
-Repetition of visual information	YES, video recap	YES, when detailed interconnection step explored

*Note that spatial orientation of Ca+ channel shown in isolated condition matches top channel

First, both groups were shown an introductory video at the start of their condition, where the major structures were very briefly pointed out on the wireframe model and small pictures of what each structure looks like are shown to depict each structure, equivalently in both conditions.

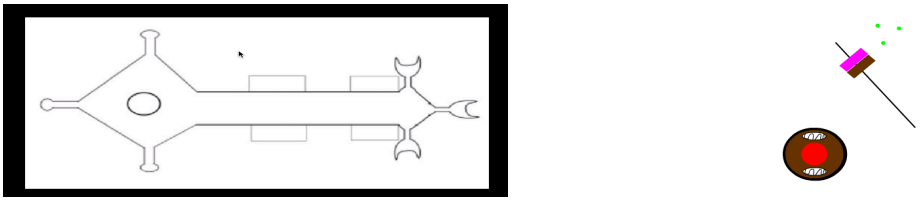


Figure 45: Introductory Video for Both Groups

Control Condition: Concept

In the control condition the location of the Top Calcium channel is pointed out in the wireframe along with the other four Ca+ channels to start the explanation of the Calcium channel topic during the treatment video:

The five locations where Calcium Channels are found are pointed out on the wireframe model below

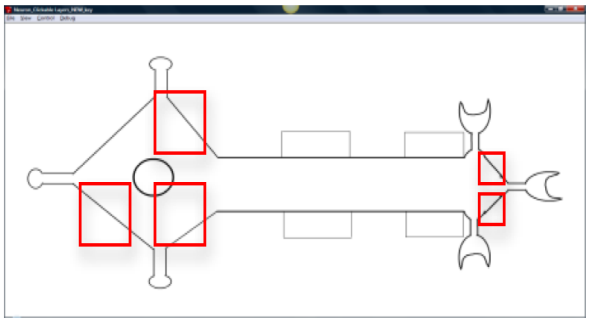


Figure 46: Locations of Ca+ Channels on Wireframe

An animated video of the major steps in the Calcium channel opening, Ca+ ions flowing in, and the channels closing are displayed with audio accompaniment (screencaptures below) :

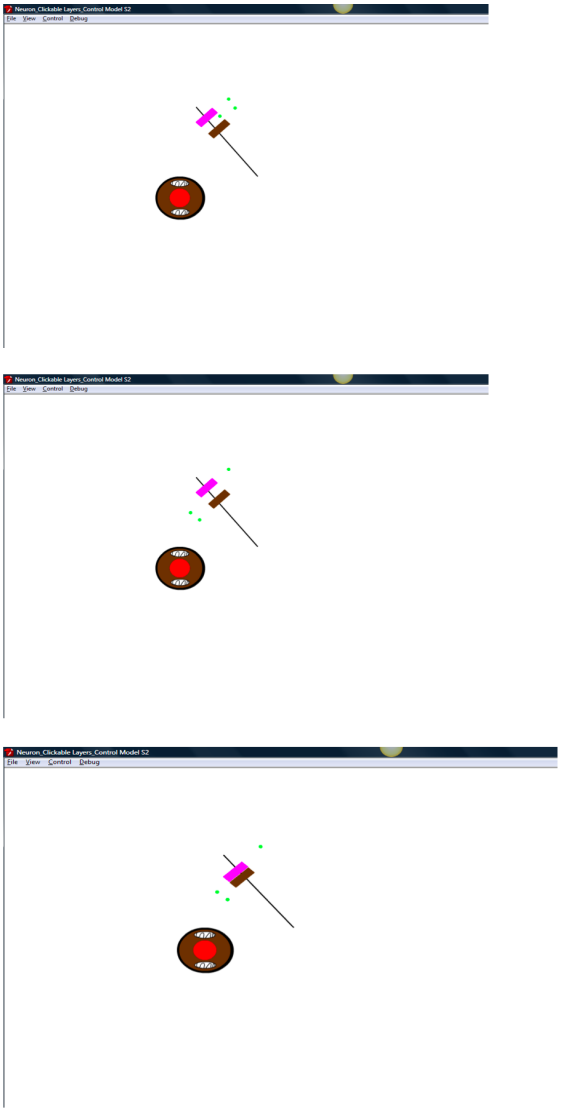


Figure 47: Screenshots of Isolated Condition Calcium Channel Opening/Closing Animation

The verbal accompaniment is as follows is identical to the experimental condition.

*This verbal transcript and the animated video are repeated verbatim in the recap section for the control section.

Experimental Condition: Concept

The experimental treatment begins with an animated video of the steps of Ca+ Channel concept using the integrated neuron:

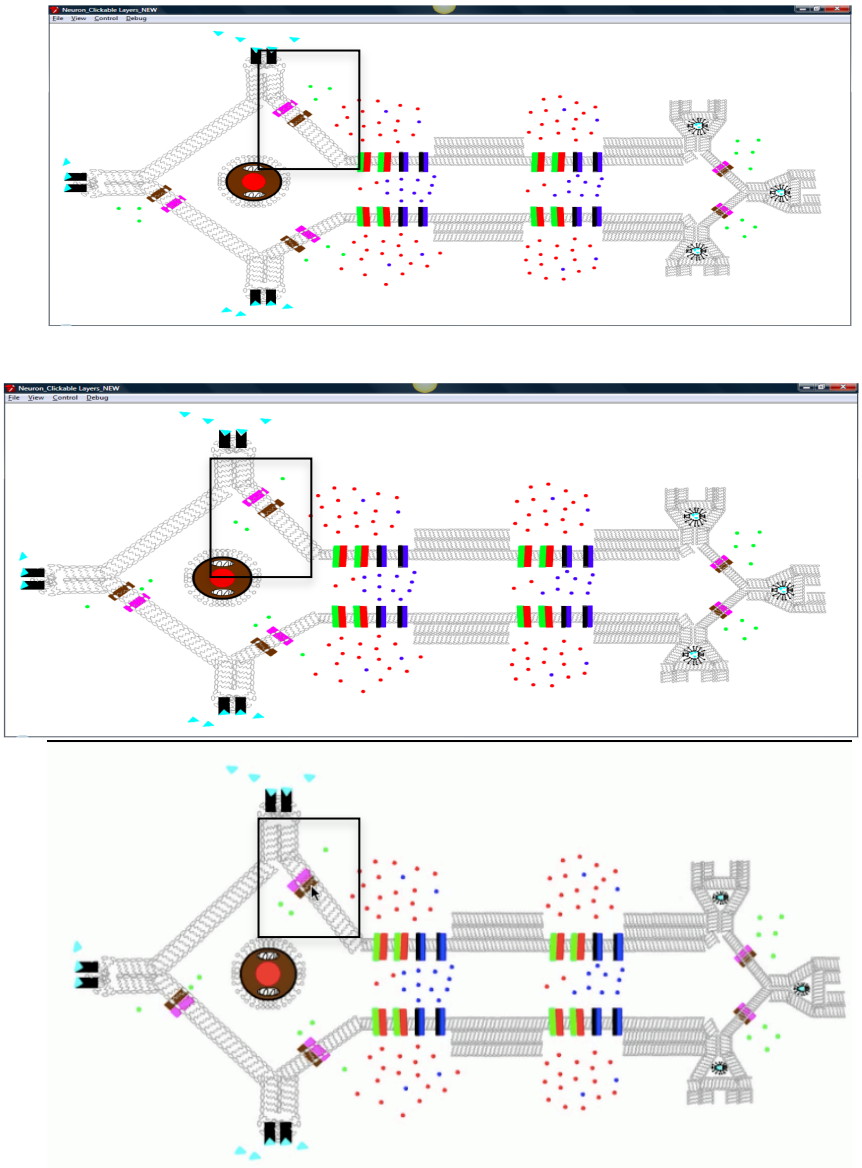


Figure 48: Screenshots of Integrative Condition Calcium Channel Opening/Closing Animation

Also, please note that the experimental group shows phospholipids surrounding the membrane of the calcium channels, while the control does not. This is part of the elaboration (see next section)

of the concept, the Calcium channel itself, the main concept, is displayed equivalently in both groups. The corresponding auditory accompaniment is as follows is essentially identical to the transcript used for the control Calcium condition.

Please note that while the experimental conditions displays more Calcium channels and points them out gesturally and verbally acknowledges these channels, this is not part of the core information for the top Ca+ channel, and is part of the elaboration of the Top Ca+ Channel concept.

Unlike the control, where the visuals and verbal for the Calcium channel concept are repeated in a recap video, this information is replicated almost identically in the detailed interconnection step that is explicit in the experimental, but not the control, that Calcium ions trigger the synaptic bouton to open at the end of the Neuron:

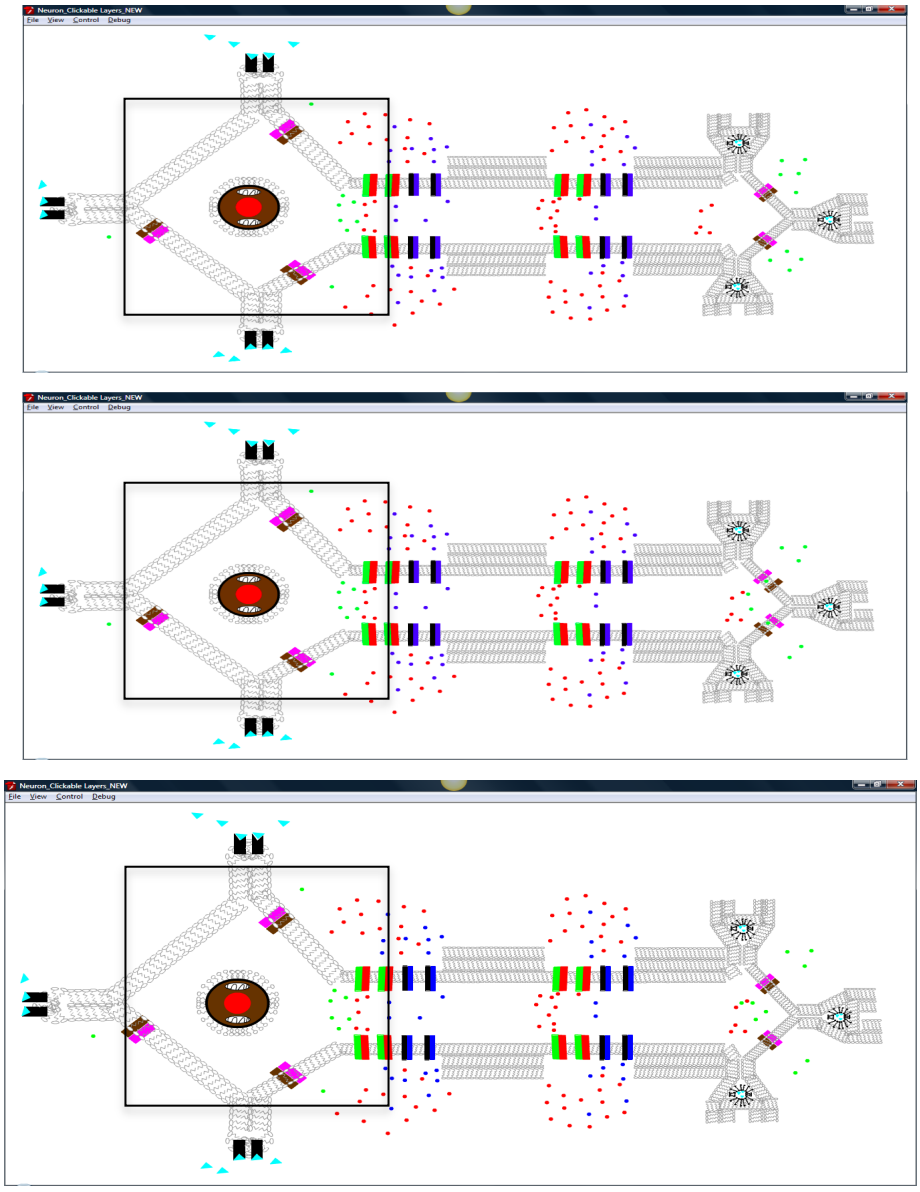


Figure 49: Screenshots of Integrative Condition Calcium Channel Concept Elaboration Animation

The corresponding auditory accompaniment is essentially identical to the transcript used for the control Calcium condition recap video. Let's also dissect the visually and verbal information used to elaborate the Calcium channel concept in both conditions, which is *not* equivalent visually or verbally.

Table 5: Compare/Contrast Elaboration of Calcium Channel Opening/Closing Concept

	Isolated Representation	Integrated Representation
Verbal		
-Process of Ca+ congregating and opening Na+ channel @ hillock	*Less detailed verbal description*	*Detailed verbal description*
Visual		
-Process of Ca+ congregating and opening Na+ channel @ hillock	*None, but are shown location of bottom 2 channels on wireframe*	*Explicit animation of process*

Control Condition: Elaboration

The interconnection that Calcium ions from the channels move toward the AP Channels and cause them to open, is described verbally and with few details right before the AP Channel animation begins as follows:

"Dendritic signals mediated by Calcium are integrated right before the first set of charge gated sodium channels, opening them"

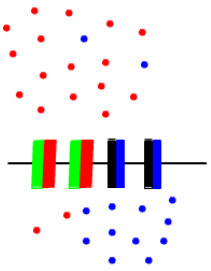


Figure 50: Isolated Condition Action Potential Screenshot

The locations of the other four Ca+ channels on the wireframe, in addition to the top Ca+ channel, are also pointed out during control treatment, post introduction:

The five locations where Calcium Channels are found are pointed out on the wireframe model below

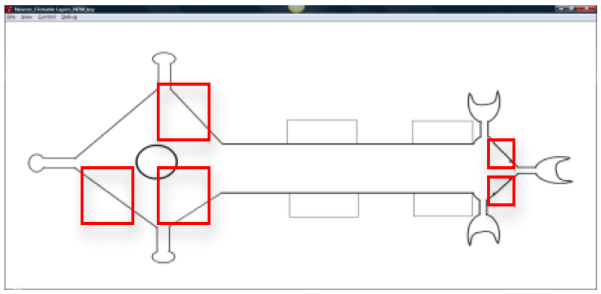


Figure 51: Locations of Ca+ Channels on Wireframe as part of Elaboration

Experimental Condition: Elaboration

The experimental condition was explicitly shown using the integrated neuron, Calcium ions moving together toward the axon hillock, congregating and trigger the AP channels to open:

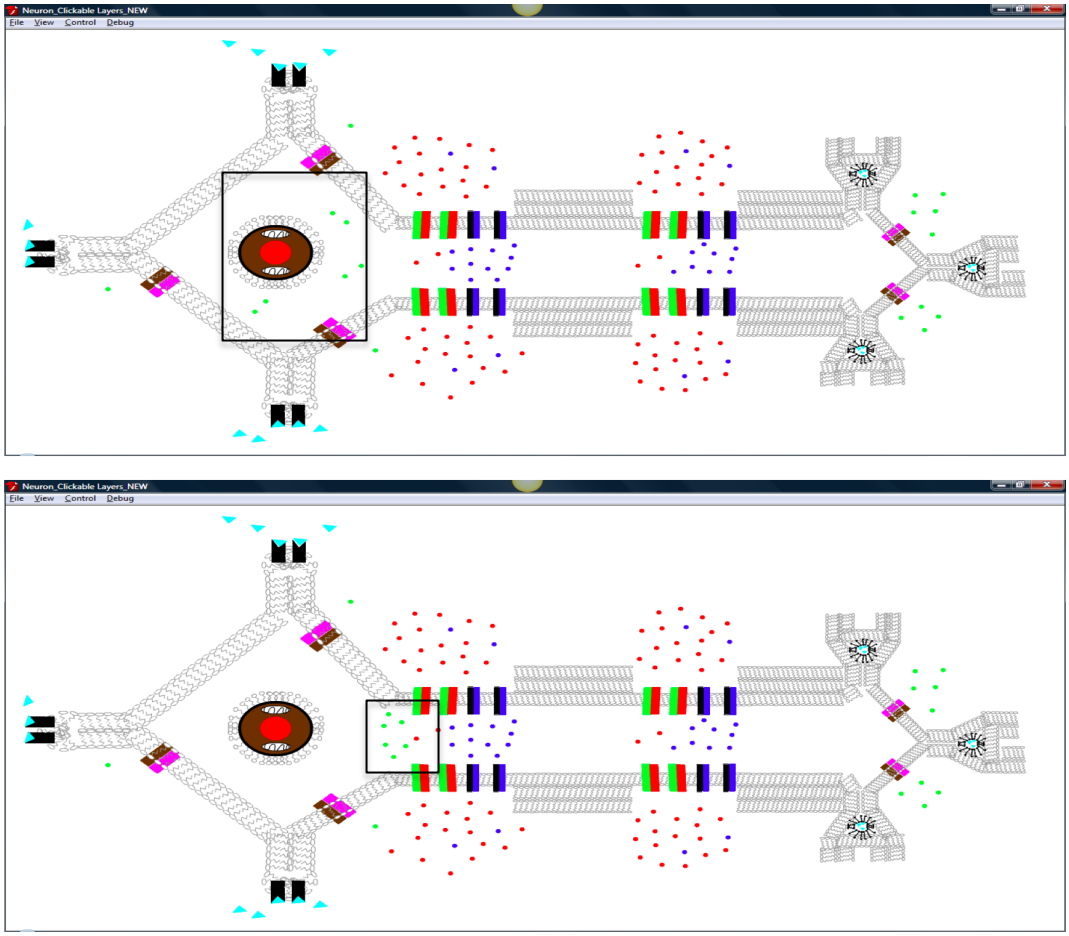


Figure 52: Integrated Condition Calcium Channel Elaboration

The auditory accompaniment that followed this animated depiction of Ca+ ions triggering the axon hillock to open explicates these events:

> "The positively charged calcium ions that just entered the neuron thru these calcium channels, begin to move together towards this area here at the start of the axon, right before the first set of sodium and potassium channels, forming a cluster of positive charge"

It is also conceivably to consider other interconnections as elaborations on the Ca+ Channel concept such as C-INT5., that sodium triggers Calcium channels to open, or C-INT.8, that the cluster of Ca+ ions inflowing at the synaptic bouton cause the synaptic-vesicle-synaptic bouton

merger. These other elaborations follow a similar verbal and visual format to the Ca+ axon hillock trigger interconnection explained above for both the control and experimental conditions.

Case Study : *AP Channels Opening/Closing Concept*

Comparison of what information was presented to both groups for the Action Potential (AP) channel is depicted in the chart below:

Table 6: Compare/Contrast AP Channels Concept for Conditions

	Isolated Representation	Integrated Representation
Verbal		
-Open, closing of channels	YES-SAME	YES-SAME
-Location of Top AP Channel	Mentioned in introduction Mentioned in lesson w/wireframe	Mentioned in introduction Shown explicitly in animation
-Repetition of verbal information	YES, video recap	Similar transcript when discussing 2nd set of AP channels opening (interconnection step)
Visual		
-Open, closing of channels	YES, but no phospholipid bckgrnd.	YES, and phospholipid bckgrnd.
-Locations of Top AP channel	*Pointed out on wireframe only in introduction and in lesson	Pointed out on wireframe only in introduction and on integrated neuron in lesson
-Repetition of visual information	YES, video recap	Not the first channel, but visuals repeated in depicting second set of AP channels opening

*Note that spatial orientation of the AP channel shown in isolated condition matches top AP channel

First, both groups were shown an introductory video at the start of their condition, where the major structures were very briefly pointed out on the wireframe model and small pictures of what each structure looks like are shown to depict each structure, equivalently in both conditions, as with the calcium channel concept.

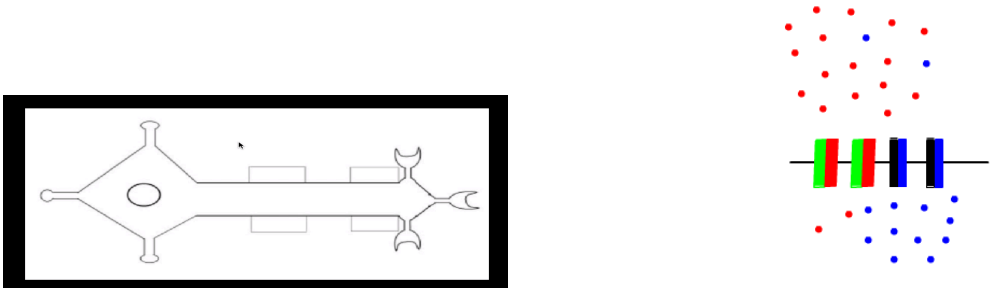


Figure 53: Introductory Video for Both Groups, AP Channel

Control Condition: Concept

In the control condition the location of the Top AP channel, in addition to the other three channels, are pointed out in the wireframe to start the explanation of the AP channel topic during the treatment video:

The four locations where Sodium and Potassium Channel Action Potential Channels are found are pointed out on the wireframe model below :

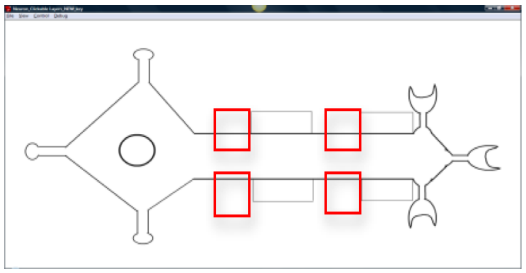


Figure 54: Locations of AP Channels on Wireframe

An animated video of the major steps in the AP Top channel opening, Na+ ions flowing in, Potassium Ions flowing out, and the AP channels closing are displayed with audio accompaniment (screencaptures below):

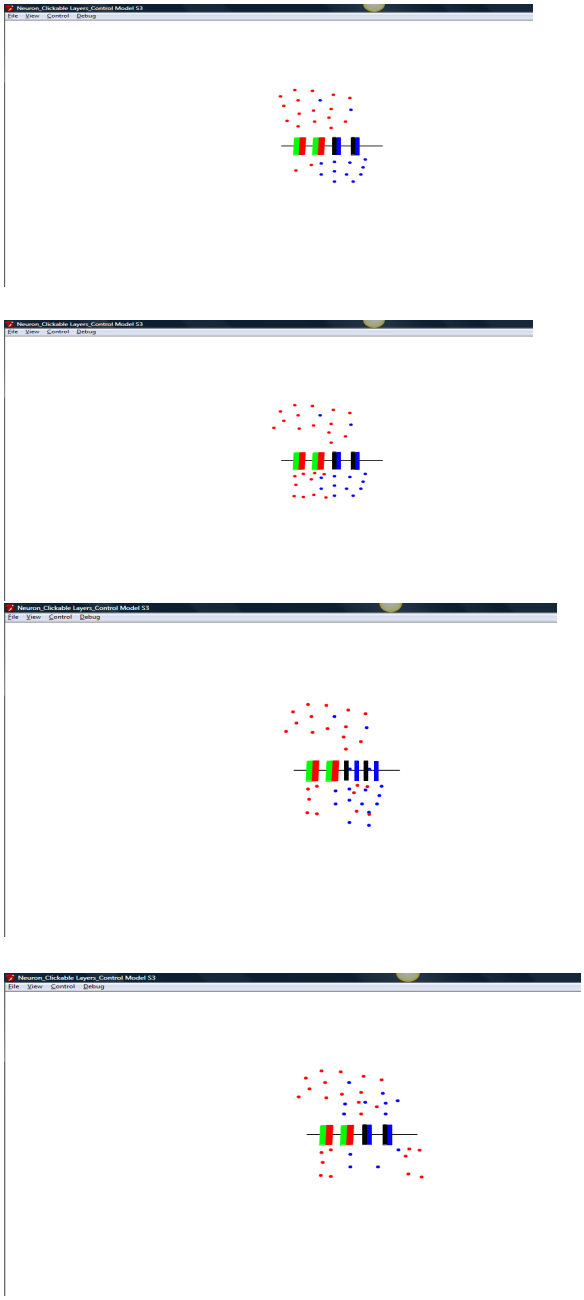


Figure 55: Isolated Condition Action Potential Channel Animation

The verbal accompaniment which follows is identical to the verbal transcript in the experimental condition for this concept. *This verbal transcript and the animated video are repeated verbatim in the recap section for the control section.

Experimental Condition: Concept

The experimental treatment begins with an animated video of the steps involved with the AP Channel concept using the integrated neuron:

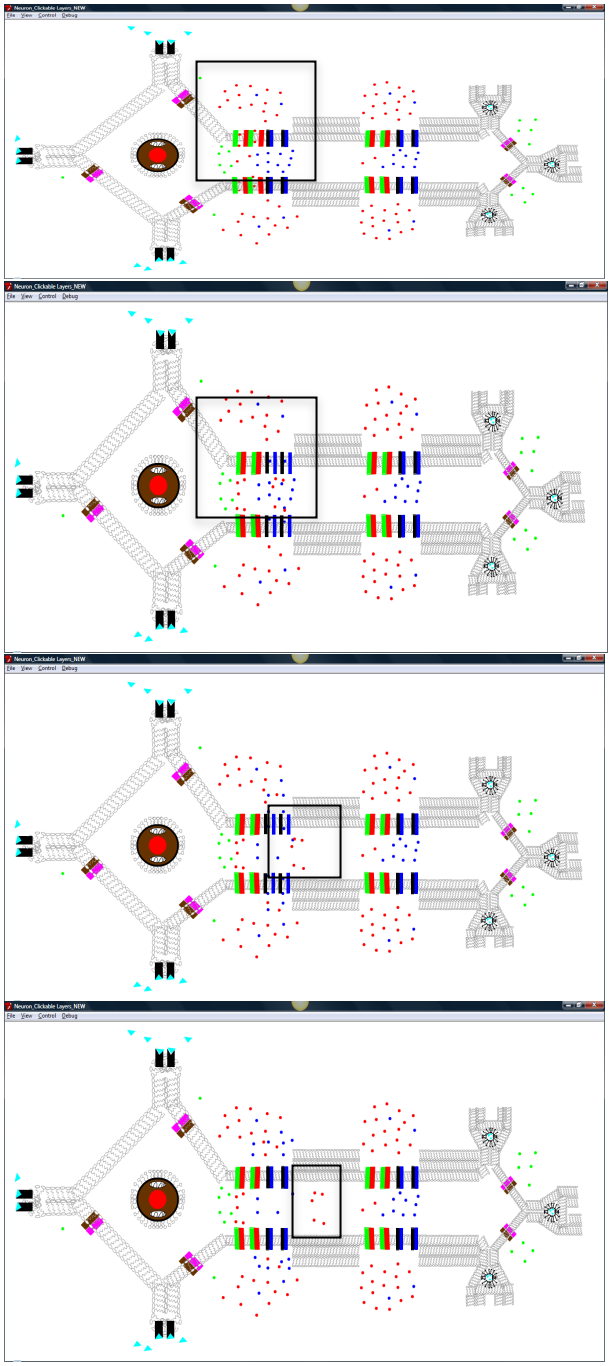


Figure 56: Integrated Condition Action Potential Screenshots

Also, please note that the experimental group shows phospholipids surrounding the membrane of the AP channels, while the control does not and also displays the bottom most AP channels in addition the top AP channels with the corresponding animation. The phospholipid bilayer displayed along the membrane and the bottom AP channels and corresponding animation are part of the elaboration (see next section) of the concept, the single AP channel (top) itself and its corresponding animation, the main concept, is displayed equivalently in both groups.

The corresponding auditory accompaniment is essentially identical to the transcript used for the control AP condition. Please note that while the bottom channels are described briefly in the transcript, these are part of the elaboration of the concept, are not part of the concept grading rubric for the AP channel. Explicitly referring to "top" Na+/K+ channels in the experimental transcript is balanced by pointing these channels out verbally on the wireframe in the control transcript.

Unlike the control, where the visuals and verbal descriptions for the AP channel concept are repeated in a recap video, this information is replicated almost identically in the detailed interconnection step that is explicit in the experimental, but not the control, that Sodium ions from the first AP trigger a second AP at the second set of AP channels (steps not shown, please see Appendix G):

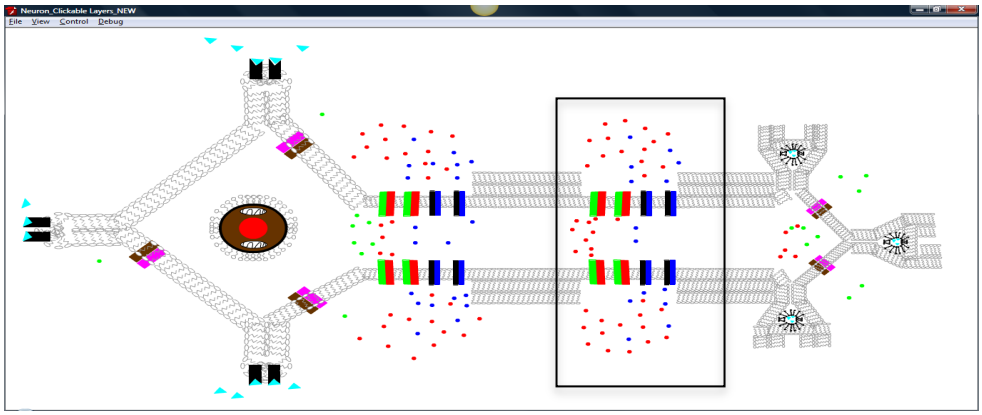


Figure 57: Repeat of Action Potential in Integrative Condition

The corresponding auditory accompaniment is as follows is essentially identical to the transcript used for the control AP condition recap video. Again, while the bottom channels are described briefly in the transcript, these are part of the elaboration of the concept, are not part of the concept grading rubric for the AP channel. Overall, it should be clear the Top AP Channel concept has been presented equivalently both visually and verbally to both groups. The grading rubric used to grade student essay responses regarding the AP Channel concept is the same for both conditions, and each group has an equivalent opportunity to score points for this concept according to the information presented:

Let's also dissect the visually and verbal information used to elaborate the AP channel concept in both conditions, which is *not* equivalent visually or verbally.

Table 7: Elaboration of AP Channel Opening/Closing Concept

	Isolated Representation	Integrated Representation
Verbal		
-Sodium Moving thru Myelin Sheath from one AP channel set to the next	Less detailed verbal description	Detailed verbal description
Visual		
-Sodium Moving thru Myelin Sheath from one AP channel set to the next	None, but shown locations of other three AP channels along neuron on wireframe	Explicit animation of process

Control Condition: Elaboration

The interconnection that Sodium ions from the first AP channel flow along the myelin sheath and then trigger an AP at the second set of AP channels is verbally described with few details as follows in the control treatment right after the AP animated video has finished:

> "As this is occurring, the positive Sodium ions that previously entered the axon, dissipate along the axon, generating action potentials, further along the axon as the Potassium channels close"

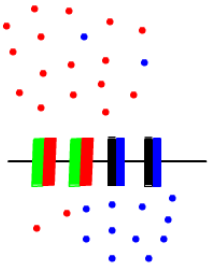


Figure 58: Isolated Condition Action Potential Screenshot

The locations on the wireframe for the other three AP channels are also pointed out during control treatment, in addition to the top AP channel, post introduction

The four locations where Sodium and Potassium Channel Action Potential Channels are found are pointed out on the wireframe model below :

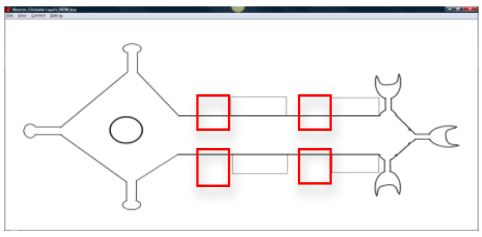


Figure 59: Locations of AP Channels on Wireframe

Experimental Condition: Elaboration

The experimental condition was explicitly shown using the integrated neuron, AP ions moving together toward the second set of AP channels, triggering them to open:

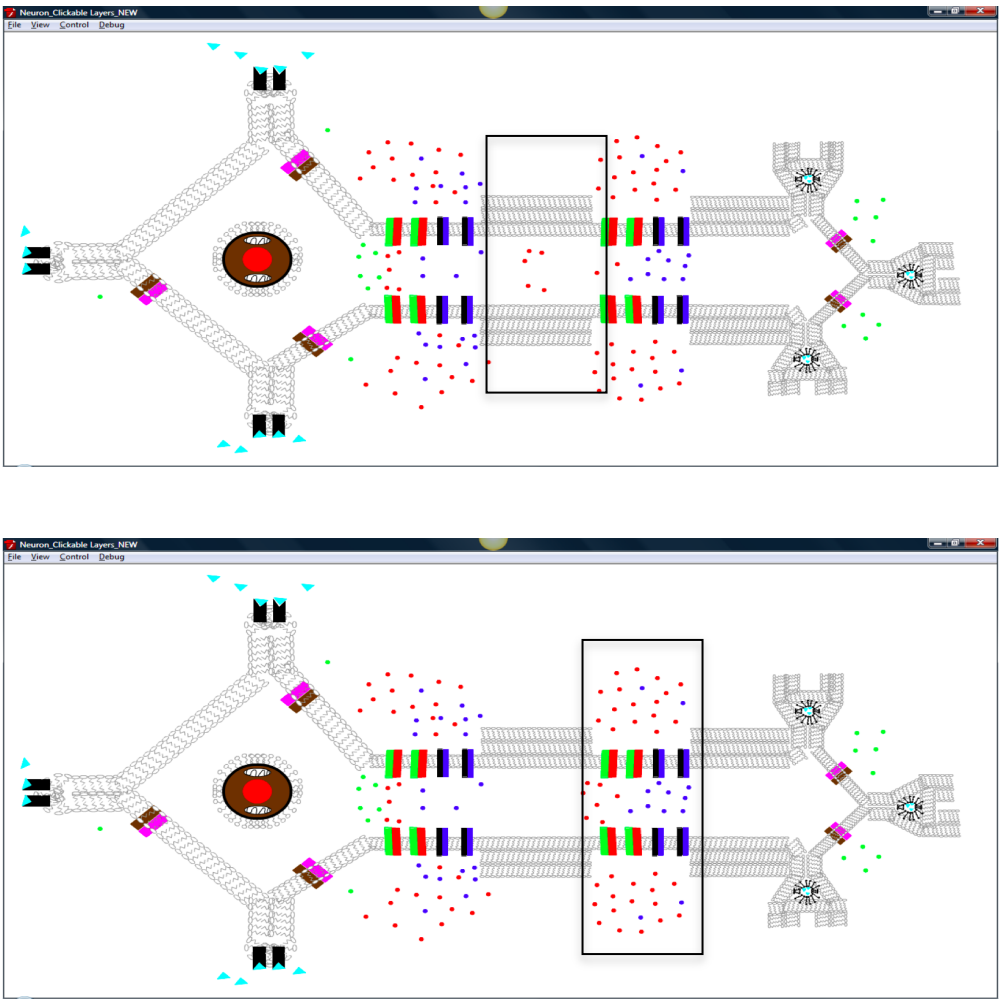


Figure 60: Integrative Condition AP Elaboration

The auditory accompaniment that followed this animated depiction of Na+ ions from the first AP channel triggering the second AP channels to open:

> "See how these positive sodium ions can easily pass from one set of Sodium channels to the next set of Sodium channels, because these stacks of phospholipids at the top and the bottom, insulate and prevent these positive ions from leaking outside the axon and the

neuron. Eventually, this cluster of positive Sodium Ions, reaches this second set of sodium and potassium channels and the action potential repeats itself"

It is also conceivably to consider other interconnections as elaborations on the AP+ Channel concept such as C-INT4., that sodium ions from the second AP channel are insulated by the myelin sheath from leaking as they travel to the end of the neuron, or C-INT5., that sodium triggers Calcium channels to open. These other elaborations follow a similar verbal and visual format to the Ca+ axon hillock trigger detailed interconnection explained above for both the control and experimental conditions.

Independent Variables

The type of neuroscience cellular stop frame animation instructional videos presented, isolated (control) or integrated (experimental) was the independent variable.

Dependent Variables

A. A pretest was administered before students watched the instructional videos, to ascertain, in conjunction with a post-test survey about their neuroscience background, whether they had high, or low prior neuroscience knowledge, in order to ensure equivalency among groups. Additionally, students filled out a post-test survey regarding their gender, undergraduate major and any previous courses taken in the field of neuroscience.

Scoring :

The students were grouped into low and high pretest score groups. A low pretest score meant the student did not display any relevant knowledge about the neuron or action potential. If the student displayed some knowledge they were automatically placed in the high pretest score group. If it was unclear if a student was demonstrating knowledge of the neuron in some capacity, their post-test survey was used, and if they took neuroscience courses in college or beyond, they were placed in the high group.

B. There are four measures of learning which comprise the assessment :

These measures are scored according to various rubrics, where details and concepts receive a point value from .25 to 2, depending on the importance of the detail. Please see the detailed rubrics in the **Appendix K for detailed information about how each sub-section here is scored.*

**It is important to note questions are generally arranged from most difficult (essay), difficult (free response/what if), and moderate difficulty (diagram labeling), and students are not allowed to go back to a question once they answer it*

4. Free response essay questions, one which instructs the student to explain the steps of signal transmission in the neuron drawing based upon the instructional materials shown in terms of cellular structures and also any steps not described in the instructional materials that are logically necessary for the process to work and make sense. Please see Appendix K, for text of essay prompt.

Scoring:

Students essays were scored on a scale of 0-8, categorically, 1 point was awarded for any indication of knowledge of the 8 detailed interconnection concepts enumerated previously (see appendix K for more details), *a cell detailed interconnection categorical sub-score*. Additionally, students were given point values for each cellular detailed interconnection they denoted, according to the rubric in the appendix K, a *cellular detailed interconnection continuous subscore*.

Students essays were also scored on a scale of 0-7, categorically, 1 point was awarded for any indication of knowledge of the 7 *subcomponent* concepts in the lesson (see appendix K for more details), *a subcomponent categorical sub-score*. Additionally, students were given point

values for each *subcomponent* they denoted, according to the rubric in the appendix K, a *subcomponent continuous sub-score*.

Some of the detailed information pertinent to one concept may also be pertinent to another, hence points may be awarded for details the student provides multiple times across all the concepts (detailed interconnections and subcomponents) which involve this information.

5. Individual expository free response short answer questions about signal transmission concepts that were visual and verbally explicit in the integrated *cellular* signal transmission animations (experimental condition), but students shown the isolated *cellular* signal transmission animations (control) would have to chunk by mentally integrating the neuronal *cellular* components they were shown, here 6 of the 8 key detailed interconnections in the essay rubric. Please see Appendix K, for examples.

Scoring:

Scoring for the 6 expository free response questions, follows the same procedure as the essay, students are categorically given credit for basically getting the question correct, and also given a more detailed point value for each concept they get correct.

Students answers are graded on details that are derived from the 8 detailed interconnections (the cellular detailed interconnection sub-scores), detailed versions given to the experimental group only, and details which are derived from the less detailed versions of these detailed interconnections given to the control group, where applicable. For example, the two concepts below both deal with calcium causing sodium channels to open, but the detailed interconnection version has specific details about calcium ions clustering together from various channels right before the first set of channels, where in the control group, it simply states with few details that "dendritic signals mediated by calcium channels" are "integrated" before the first set of sodium channels.

Interconnection #1 Control version : Less detailed depiction

Dendritic signals[1] mediated by Calcium[2] are integrated right before the first set of charge gated sodium channels[1], opening them[1], which begins a series of events called the action potential[1]

Interconnection #1 Experimental Version : More detailed depiction

1. Calcium triggers Sodium Channels to open and start AP

Model Answer :

Positive[.5] calcium ions entering the neuron[1] from the (three) calcium channels[.5] near the dendrites of the neuron[.25], flow together along the pre-axon (Soma) area of the neuron[1.5], and form a cluster (converge) together[2] of positive charge[1] near the first set of sodium and potassium channels[1], which triggers the top[.25] and bottom[.25] sodium channels to open[1] starting the process of the action potential[.5].

Accordingly, if a student gives the detailed version of this concept (Calcium ions clustering and triggering sodium channels to open), they will receive credit for the detailed version of this interconnection, according to the detailed version grading rubric, but will also receive credit for the less detailed version of this concept, according to what details in the rubric for the less detailed version of the interconnection they detail. Students giving the less detailed version of this concept do not receive credit for the detailed version. This dual less detailed/detailed presentation pertains also to C-INT.2,4 and 5.

The whole point of this is to tease apart when students explain certain key interrelationships between subcomponents in the lesson with few details (isolated, control condition derived) instead of a great amount of detail (Integrated presentation, experimental condition derived).

6. Individual free response short answer “What If” questions where students have to engage in thought experiments and manipulate their signal transmission mental models in order to predict the outcomes of scenarios where the values of key *cellular* entities comprising the neuron (such as the number calcium channels, amount of myelin) are altered. Please see Appendix K, for examples.

Scoring:

Similar to the essay and the expository free response sections students were given categorical and continuous (a point value) credit for each of their responses, using the 8 cellular detailed interconnection scoring rubric. Analyses were done for less detailed versions of the detailed interconnections and for details which were only peripherally related to the main proximal cause using both the detailed interconnection and subcomponent rubrics, but were removed from the final analysis.

7. Individual neuron wireframe diagram-labeling questions which require the student to label a neuron wireframe with arrows and other symbols to denote where certain important cellular events occur, such as where positive charges enters or exits the neuron, or how sodium enters and flows in the neuron, which are a mix of content that is visually and verbally explicit in both the experimental and control groups and content that is visual and verbally explicit in the integrated signal transmission animations (experimental condition), but not in the control. Please see Appendix K, for examples.

Scoring :

Students are awarded credit for arrows and plus signs (depending on the question), that were concepts that were visually depicted in both conditions, subcomponent points, black arrows in the grading rubric. Please note that the experimental group did not have any explicit arrows denoting the directions of how the ions were flowing in the neuron. For example, the first calcium channel in the neuron and how it works is depicted in both conditions explicitly. Students are also awarded credit for arrows and plus signs for spatial concepts that were explicit in the experimental group, but the control condition was only shown abstractly on the wireframe. For example, the control was shown that calcium channels are located at 4 other locations, other than the 1st location which they were explicitly shown an animation of, orange arrows in the rubric. However, while these 4 other locations in the control were shown on the wireframe abstractly using boxes:

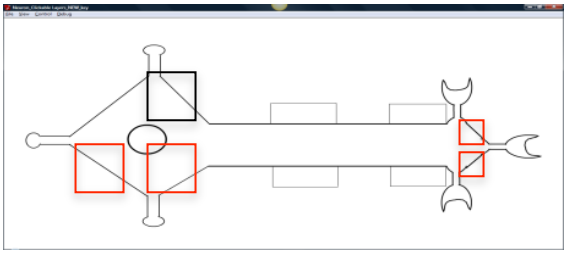


Figure 61: Locations of explicit(black) and wireframe only(red) locations of Ca+ Channels

There was no explicit animation of the calcium channels opening and closing and having calcium ions flow thru at these 4 locations, as in the experimental group. Hence, the arrows denoting the motion of calcium at these 4 locations, are scored under a "wireframe detailed interconnection" subscore.

Last, arrows and plus signs which denote spatial concepts in the lesson that require the student to mentally animate the movement of ions that were not shown explicitly or on the wireframe, were under the "mental animation" subscore. For example, the movement of sodium from one set of action potential channels to the next thru the myelin sheath is not explicitly depicted, but described with few details in the control condition, red arrows in the grading rubric.

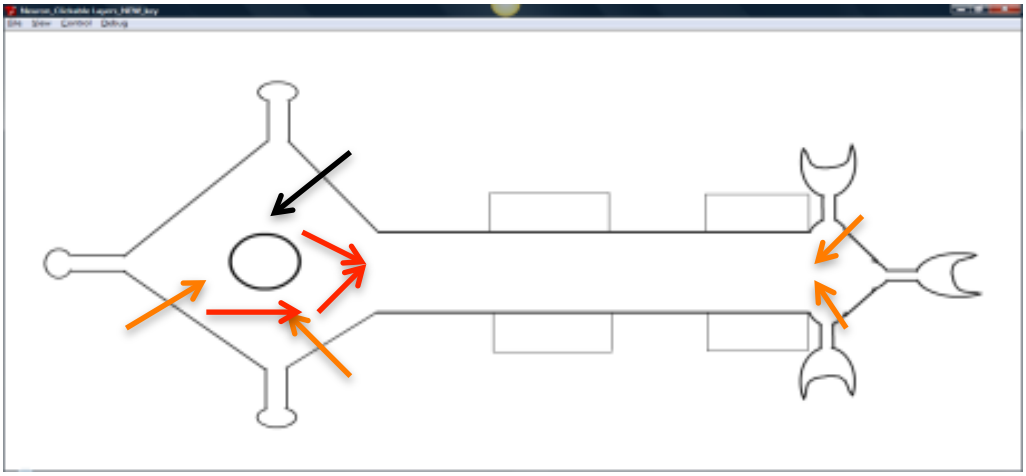


Figure 62: Diagram of Model answer to Ca+ Channel Ion Flow Diagram Labeling Question

Inter-rater Reliability

15 of the 32 assessments were selected randomly for inter-rater reliability check against my own grading by a graduate student voluntarily recruited from the Neuroscience and Education Department at Teachers College. The student received training in how to score the data using the rubrics and was kept blind to the types of conditions. The Spearman's rank correlation coefficient was calculated for each of the major sub-scores of the test, please see tables below, and was in the area of fairly strong to very strong agreement for all sub scores, with most scores between .8 and .95.

Table 8: Rater Reliability for Free Response Essay

Essay	Spearman's rho
Cell Conc. Int. Total Cat.	.944
Cell Conc. Int. Total Cont.	.925
Subcomp Total Cat.	.981
Subcomp Total Cont.	.909

Table 9: Rater Reliability for Free Response Short Answer Questions

FR-E-SA	Spearman's rho
Cell Conc. Int. Total Cat. (detailed)	.930
Cell Conc. Int. Total Cont. (detailed)	.943
Cell Conc. Int. Total Cat. (less detailed)	.918
Cell Conc. Int. Total Cont. (less detailed)	.875

Table 10: Rater Reliability for Free Response What-If Questions

FRE : What If	
Proximal Conc. Int. Total Cat.	.909
Proximal Conc. Int. Total Cont.	.930

Table 11: Rater Reliability for Free Response Diagram Labeling Questions

Diagram Labeling	
Subcomponent Total Cont.	.842
Wireframe-Con-Inter Total Cont.	.933
Mental Animation-Conc-Inter Total Cont.	.808

Procedure

Teacher's College Graduate Students in Online Course were randomly assigned to either the control or experimental condition and e-mailed instructions about how to access the corresponding experimental website and the due date and submission requirements for the experiment. Their participation in the experiment was part of their mandatory online research participation requirements which were stated in their course syllabi. Students were instructed to complete the experiment in one sitting in a quiet place with minimal to no distractions. They went go to their assigned experimental website, fill out the consent form available on the website, watched the videos and then downloaded the assessment. Students then completed the assessment on their respective computers, using MS Word, and e-mailed the assessment and consent form to my gmail.com e-mail address (cogsci7@gmail.com). Shortly after all students have submitted their assessments and consent forms, a debriefing form was e-mailed to all students.

Results

Each category of assessment question and its subscore was treated as a dependent variable and accordingly, t-tests were conducted on each of the dependent variables displayed after each of three data tables encompassing the four major question types with significant subscores/variables in red (please see grading rubric in *Appendix K*, for scoring criteria). Since many dependent measures failed the levene's test of equality of variances, whenever a dependent measure had unequal variances, statistics to take this into account were chosen appropriately. Measures were unequal variances were assumed are marked by an asterisk.

Please note the following conventions for the data tables for this dissertation study section:

* = $p < .05$
** = $.05 > p > .01$
*** = $p < .01$

Table 12: Pre-Test Chi Square Results

Condition	Pretest Score
Isolated Visuals	L = 7/17 H = 10/17
Integrated Visuals	L = 9/15 H = 6/15

$X^2 = 1.13$
df = 1
$p = .29 > .05$

Note: Pretest Scores are reported as "Scorers in Category"/"Total Number of Scorers"

L= Low Prior Knowledge Pretest Group

H= High Prior Knowledge Pretest Group

In terms of assessment, a binary scale was used. A low pretest score meant the student did not display any relevant knowledge about the neuron or action potential. A high pretest score meant the student displayed any relevant knowledge whatsoever of the signal transmission

process in their response. If it was unclear if a student was demonstrating knowledge of the neuron in some capacity, their post-test survey was used, and if they took neuroscience courses in college or beyond, they were placed in the high group. A Chi-Square test found no significant difference among groups for the pretest, $X2$ (1, N = 32) = 1.13, p =.29, meaning there were no significant differences in terms of how many high and low pretest scorers were in each group. Hence we can assume groups were equivalent in terms of prior knowledge of the action potential.

Denotations for the remaining sections of what constitutes a low, medium and high continuous point sub-score is below each sub-score descriptor, determined by a subject matter expert in neurobiology. Notice this is in lite of the fact that given how many possibly details a person can conceivably give in a free response section, it is unreasonable to assume any student, no matter how well they learned the lesson would ever give all the possible details, or even 75% of all of them.

Table 13: Free Recall Essay Results

FREE RECALL ESSAY QUESTION

Condition	Subcomp Total Cat. (y/n)	**Subcomp Total Cont. (pts.)
Isolated Visuals	**M** = 3.88/7 SD = 1.99	M = 12.35/49 SD = 8.25
Integrated Visuals	**M** = 4.80/7 SD = 1.32	M = 19.39/49 SD = 9.08
	t = -1.551 df = 30 p =.141	t = -2.298 df = 30 p < .03 Coh. D = .84

Note: Means are presented in the format "Mean Score for DV"/"Total Possible Points for DV"

Subcomp Sub Total Cat. : Total Sub-components Only Categorical Score for Essay

Low Score (L): 1-2

Medium Score (M): 3-4

High Score (H): 5-7

Subcomp Sub Total Cont. : Total Sub-components Only Continuous Score for Essay

Low Score(L): 0-6

Medium Score(M): 7-15

High Score(H): 16-57

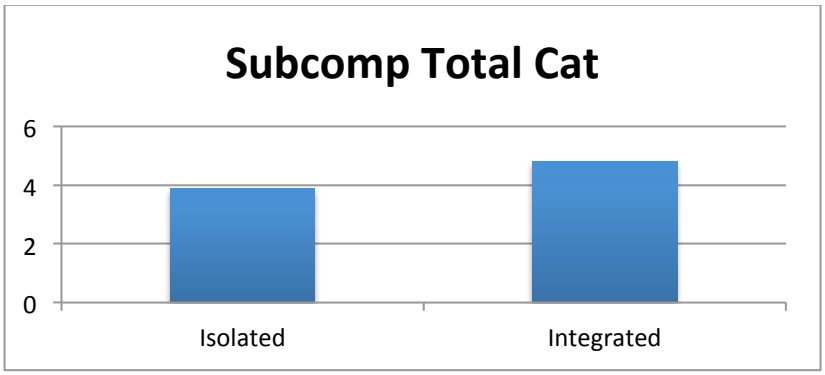


Figure 63: Subcomponents Total Categorical Score Graph

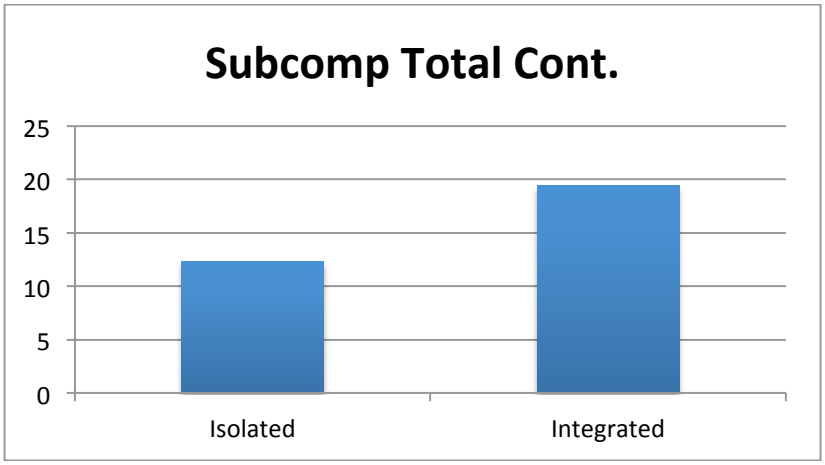


Figure 64: Subcomponents Total Continuous Score Graph

Given the importance of this section to the overall analysis, below are sample student responses for each condition to serve as case studies to compare both conditions against:

Control Case Study response:

The steps of signal transmission occurs in a methodical manner. Dendrites, and boutons allow for electric channel and communication. Synapses are the connection between the axon and the dendrite and this is where synaptic information is exchanged. Information is also passed along the axon body and phosphorous head with hydrogen tails help move information along. There are exchanges of potassium and sodium in dendrite channels.

Experimental Case Study response:

First the neurotransmitter binds to the dendrite. This triggers the calcium channels in the dendrite to open, allowing positive calcium ions to flow into the neuron. Eventually the calcium channels close. These calcium ions travel towards the axon of the neuron. The concentration of the positive calcium ions triggers the sodium channels in the axon to open. Positive sodium ions flow into the axon. Eventually the sodium channels close. The collection of positive ions triggers

the potassium channels to open. Positive potassium ions flow into the axon. Eventually the potassium channels close. The sodium and potassium ions move down the axon away from the dendrite aided by the phospholipid material that lines the neuron. The ions trigger the second set of sodium channels to open. Positive sodium ions flow into the axon. Eventually the sodium channels close. This concentration of positive ions triggers the second set of potassium channels to open. Positive potassium ions flow out of the axon, thus balancing the ratio of positive ions in and outside the neuron. Eventually the potassium channels close. At the same time the sodium ions continue down the axon towards the very end where there is more phosolipd material and bootons (spelling?). The concentration of sodium ions triggers the calcium channels in the axon to open. Positive calcium ions flow into the axon. Eventually the calcium channels close. The calcium ions trigger the bouton to merge with the phospholipid material surrounding the vesicle which contains a neurotransmitter. This merging allows a pathway for the neurotransmitter to be released from the axon thus the neuron. If there is another neuron nearby, the neurotransmitter can be absorb into that neuron's dendrite and the process will begin all over again.

Table 14: Free Recall Essay Detailed Interconnections Results

FREE RECALL ESSAY QUESTION

Condition	***Cell Detailed Inter Total Cat. (y/n)	***Cell Detailed Inter Total Cont. (pts.)
Isolated Visuals	**M = .5/8** SD = .874	M = 1.16/75 SD = 2.18
Integrated Visuals	**M = 4.87/8** SD = 2.031	M = 32.25/75 SD = 17.25
	t = -7.77 df = 18.52 p < .001 Coh. D = 2.54	t = -6.95 df = 14.39 p < .001 Coh. D = 2.09

Note: Means are presented in the format "Mean Score for DV"/"Total Possible Points for DV"

Cell Detailed Inter Total Cat.: Total Cellular Categorical Detailed interconnection Score for Essay

Cell Detailed Inter Total Cont.: Total Cellular Continuous Detailed interconnection Score for Essay

L = 0-7, M = 7-15, H = 16-75

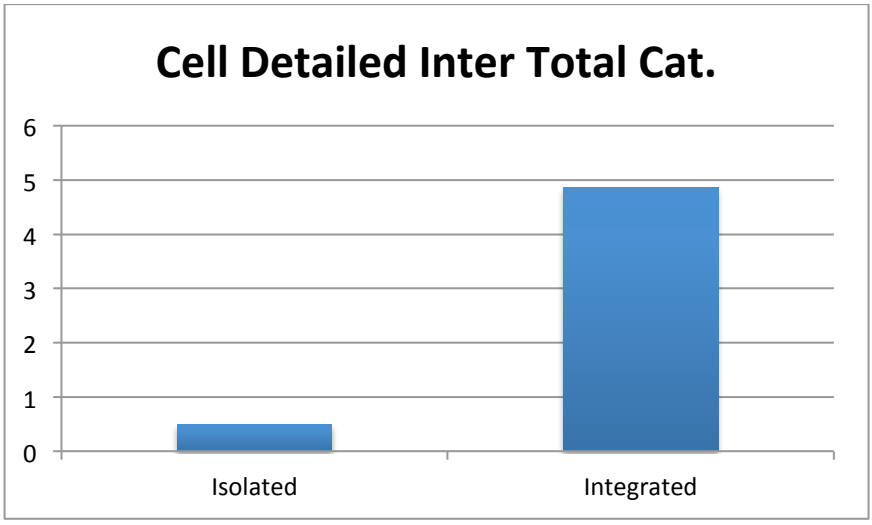


Figure 65: Cellular Detailed Interconnection Free Response Essay Total Categorical Score Graph

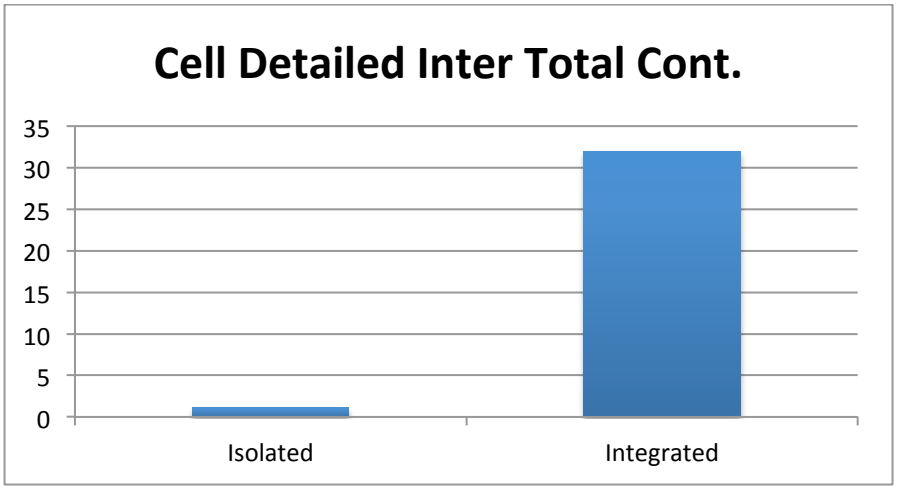


Figure 66: Cellular Detailed Interconnection Free Response Essay Total Continuous Score Graph

Independent paired samples tests, equal variance assumed did not demonstrate significant differences for the categorical subcomponent sub-score ($t = -1.551, df = 30, p > .05$), but did find highly significant differences for the ($t = -2.298, df = 30, p < .03$, Cohen's D: .84), subcomponent continuous sub-scores. The integrated group (M = 19.39, SD = 9.08) performed significantly better than the isolated group (M = 12.35, SD = 8.25) for this subsection.

Independent samples paired-tests, unequal variances assumed, demonstrated there were very highly significant differences among the groups for the categorical cellular detailed interconnection sub-score ($t = -7.77, df = 18.5, p < .001$, Cohen's D : 2.54), and continuous cellular detailed interconnection sub-scores ($t = -6.95, df = 14.39, p < .001$, Cohen's D : 2.09). Specifically, the integrated group (M = 4.87, SD = 2.031) performed significantly better than the isolated group (M = .5, SD = .874) for the categorical subsection. The integrated group (M = 32.25, SD = 17.25) performed significantly better than the isolated group (M = 1.16, SD = 2.18) for the continuous subsection.

Accordingly, the free recall essay section, demonstrated that the integrated visuals condition resulted in much more pronounced recall of the individual neuron sub-components presented equivalently to both groups, which was mediated by pronounced recall of the experimental group over the control for the interactions among the sub-components. This resulted in better chunking of all concepts in the lesson, including the concepts presented equivalently to both groups.

Table 15: Free Recall Expository Short Answer Results

FREE RECALL EXPOS. SHORT ANSWER DETAILED INTERCONNECTION QUESTIONS :

Condition	***Cell Detailed Int. Cat. (y/n)	***Cell Detailed Int. Cont. (pts.)	***Cell Less detailed Int. Cat. (y/n)	***Cell Less detailed Int. Cont. (pts.)
Isolated Visuals	M = 1.06/6 SD = .966	M = 2.82/62.5 SD = 2.88	M = 1.12/3 SD = .993	M = 3.82/14.5 SD = 4.04
Integrated Visuals	**M = 4.47/6** SD = 1.73	M = 21.85/62.5 SD = 12.63	**M = 2.67/3** SD = .617	M = 10.72/14.5 SD = 4.25
	t = -6.76 df = 21.38 p < .001 Coh. D = 2.47	t = -5.706 df = 15.29 p < .001 Coh. D = 2.08	t = -5.214 df = 30 p < .001 Coh. D = 1.97	t = -4.702 df = 30 p < .001 Coh. D = 1.72

Note: Means are presented in the format "Mean Score for DV"/"Total Possible Points for DV"

Cell Detailed Int. Cat.: Total Cellular Categorical Detailed Interconnection Score for all Expository Short Answer Q's

Cell Detailed Int. Cont.: Total Cellular Continuous Detailed Interconnection Score for all Expository Short Answer Q's,

L = 0-7, M = 7-15, H = 16-57

Cell Abs. Int. Cat: Total Categorical Less detailed Interconnection Score for all Expository Short Answer Q's

Cell Abs. Int. Cont.: Total Continuous Less detailed Interconnection Score for all Expository Short Answer Q's

L = 0-3, M = 3-5, H = 7-14

*Note that some questions only had a cellular detailed interconnection version, hence there are not equal numbers of cellular detailed and less detailed question scores categorically

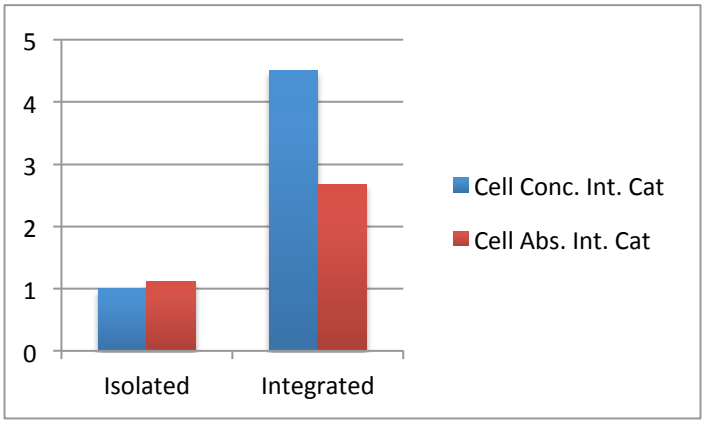


Figure 67: Cellular Detailed Interconnections Short Answer Total Categorical/Continuous Scores

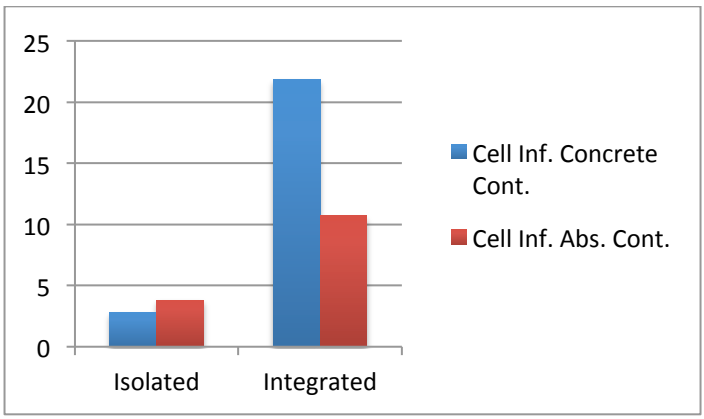


Figure 68: Cellular Less Detailed Interconnections Short Answer Total Categorical/Continuous Scores

Independent samples paired-tests, unequal variances assumed, demonstrated there were very highly significant differences among the groups for the categorical cellular detailed interconnection sub-score (t = -6.76, df = 21.38, p < .001, Cohen's D : 2.47) and continuous cellular detailed interconnection sub-scores, (t = -5.706, df = 15.29, p < .001, Cohen's D : 2.08) for the expository free response short answer interconnection section questions.

Specifically, the integrated group (M = 4.47, SD = 1.73) performed significantly better than the isolated group (M = 1.06, SD = .966) for the detailed categorical subsection. The integrated group (M = 21.85, SD = 12.63) performed significantly better than the isolated group (M = 2.82, SD = 2.88) for the detailed continuous subsection.

Also, independent paired samples tests, equal variance assumed demonstrated highly significant differences for categorical cellular less detailed interconnection sub-score (t = -5.214, df = 30, p < .001, Cohen's D : 1.97) and cellular less detailed interconnection continuous sub-scores, (t = -4.702, df = 30, p < .001, Cohen's D : .1.72). Specifically, the integrated group (M = 2.67, SD = .617) performed significantly better than the isolated group (M = 1.12, SD = .993) for the less detailed categorical subsection. The integrated group (M = 10.72, SD = 4.25) performed significantly better than the isolated group (M = 3.82, SD = 4.04) for the less detailed continuous subsection. Accordingly, the free recall short answer sections, demonstrated that the integrated visuals condition resulted in much more pronounced recall of the complex system of signal transmission, especially for interactions among the sub-components (interconnections).

Table 16: Free Recall What-If Results

FREE RECALL WHAT-IF (PROBLEM SOLVING) SHORT ANSWER INTERCONNECTION QUESTIONS :

Condition	***Proximal Cell Detailed Int. Total Cat. (y/n)	***Proximal Cell Detailed Int. Total Cont. (pts.)
Isolated Visuals	M = .71/3 SD = .686	M = 1.41/47.5 SD = 1.37
Integrated Visuals	M = 1.87/3 SD = .990	M = 7.33/47.5 SD = 5.49
	t = -3.892 df = 30 p < .005 Coh. D = 1.39	t = -4.070 df = 15.55 p < .005 Coh. D = 1.49

Note: Means are presented in the format "Mean Score for DV"/"Total Possible Points for DV"

Proximal Cell Detailed Int. Total Cat.: Total Proximal Cellular Interconnection Categorical Score for all What-If Short Answer Q's

Proximal Cell Detailed Int. Total Cont.: Total Proximal Cellular Interconnection Continuous Score for all What-If Short Answer Q's

L = 0-3, M = 3-5, H = 7-11

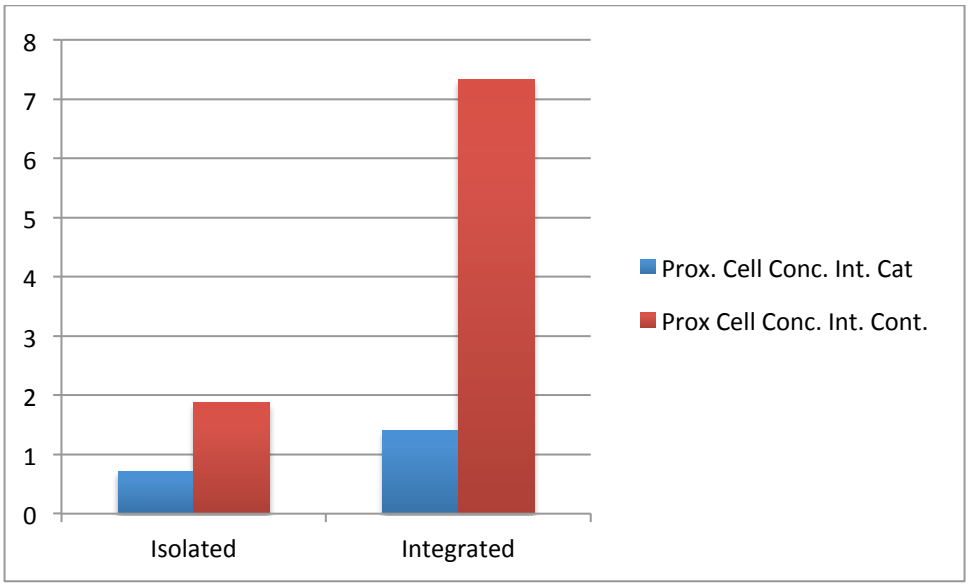


Figure 69: Cellular Detailed Interconnections What-If Total Categorical/Continuous Scores

Independent samples paired-tests, variance assumed, (t = -3.892, df = 30, p < .005, Cohen's D : 1.39) demonstrated there were highly significant differences among the groups for the proximal detailed categorical cellular interconnection sub-score, and an independent samples paired t-test, unequal variances assumed, (t = -4.070, df = 15.55, p < .005, Cohen's D : 1.49), demonstrated significant differences among the proximal detailed cellular interconnection continuous total sub-score for this What-If section. Specifically, the integrated group (M = 1.87, SD = .99) performed significantly better than the isolated group (M = .71, SD = .686) for the detailed categorical subsection. The integrated group (M = 7.33, SD = 5.49) performed significantly better than the isolated group (M = 1.41, SD = 1.37) for the detailed continuous subsection.

This proffers evidence that the aspects of mental problem solving and altering functional entities that comprise the neural signal transmission system that require a mental model which has an integrated representation of these functional sub-components are better reasoned when

these relations (interconnections) are made visually explicit in an integrated visual representation.

Table 17: Free Recall Diagram Labeling Results

DIAGRAM LABELING INTERCONNECTION AND SUBCOMPONENT QUESTIONS :

Condition	Diagram : Subcomponent Total (pts.)	***Diagram : Wireframe Interconnection Total (pts.)	***Diagram : Mental Animation Interconnection Total (pts.)	***Diagram : Wireframe + Mental Animation Interconnection Total (pts.)	***Grand Total for Subc./Wiframe Int./Mental Animation Int. (pts.)
Isolated Visuals	M=2.76/9 SD = 2.42	M =6.03/17 SD = 5.83	M = 2.47/9 SD = 2.62	M = 8.50/26 SD = 8.26	M = 11.59/33 SD = 10.74
Integrated Visuals	M=4.23/9 SD = 2.04	M = 12.17/17 SD = 5.93	M = 5.57/9 SD = 2.09	M = 17.73/26 SD = 7.57	M = 22.13/33 SD = 9.60
	t = -1.842 df = 30 p = .075 > .05	t = -2.947 df = 30 p < .01 Coh. D = 1.08	t = -3.654 df = 30 p < .01 Coh. D =2.28	t = -3.280 df = 30 p < .005 Coh. D = 1.21	t = -2.913 df = 30 p < .01 Coh. D = 1.07

Note: Means are presented in the format "Mean Score for DV"/"Total Possible Points for DV"

*Please note, that here, some subjects did not answer this question, because of technical problems with the drawing function of MS Word. Accordingly, N = 15, control, N= 14, experimental here.

Diagram Subcomponent Total : Total Subcomponent arrow labeling score for entire section

Diagram Wireframe Interconnection Total : Total Wireframe interconnection arrow labeling score for entire section

Diagram Mental Animation Interconnection Total : Total Mental Animation interconnection arrow labeling score for entire section

*Note each of the 5 individual diagram labeling questions varied in terms of how many subcomponent, wireframe/mental animation interconnections it contained

Diagram Wireframe + Mental Animation Interconnection Total : Total Mental Animation interconnection arrow labeling score for entire section

Diagram Grand Total, Subcomponent + Wireframe Interconnection + Mental Animation Interconnection Total : Total across all sections

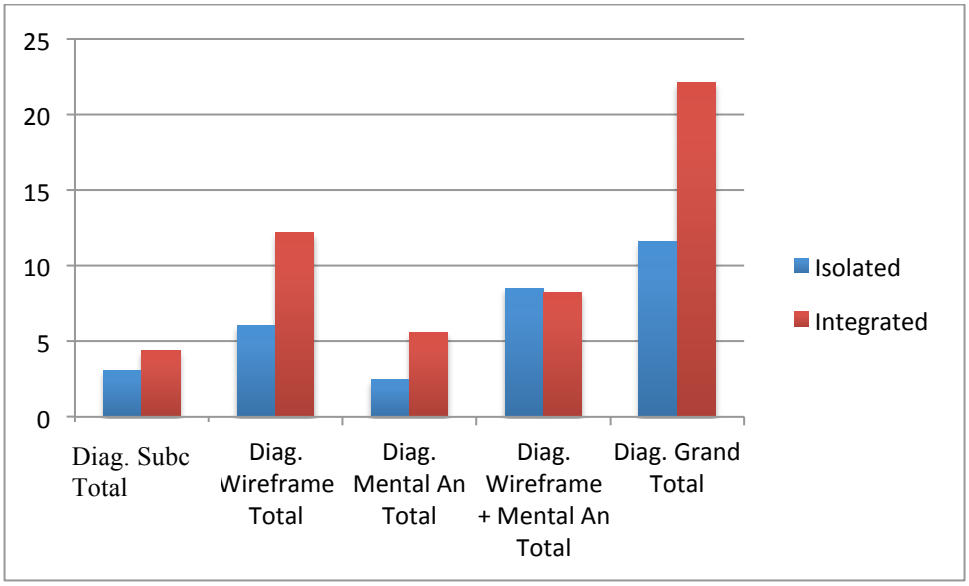


Figure 70: Cellular Diagram Labeling Sections Categorical/Continuous Scores Graph

An Independent samples paired-test, equal variances assumed, (t = -3.075, df = 27, p < .01, Cohen's D = 1.19), demonstrated there were highly significant differences among the groups for the wireframe interconnection diagram labeling questions and a t-test with unequal variances assumed, (t = -4.038, df = 27, p < .01, Cohen's D = 1.53), demonstrated very highly significant differences among the groups for the mental animation interconnection diagram labeling questions. Specifically, the integrated group (M = 12.17, SD = 5.93) performed significantly better than the isolated group (M = 6.03, SD = 5.83) for the wireframe interconnection subsection. The integrated group (M = 5.57, SD = 2.09) performed significantly better than the isolated group (M = 2.47, SD = 2.62) for the mental animation subsection.

It is noted the differences are most significant for arguably the most spatially complex task of the system, mentally animating the interactivity between sub-components, next came mentally duplicating an individual sub-component, such as an individual calcium channel along the

wireframe where red boxes denoted it should appear. No differences were found for spatial diagram labeling questions dealing with the least spatially complex aspect of this complex system, the spatial movement of ions/positive charges for individual sub-components, the subcomponent labeling questions.

An Independent samples paired-test, equal variances assumed, (t = -3.508, df = 27, p < .005, Cohen's D = 1.35) demonstrated there were highly significant differences among the groups for both the wireframe and mental animation interconnection diagram labeling questions combined, and (t = -3.082, df = 27, p < .010, Cohen's D = 1.19) for all three sub-scores, subcomponent, wireframe and mental animation, combined. Specifically, the integrated group (M = 17.73, SD = 7.57) performed significantly better than the isolated group (M = 8.50, SD = 8.26) for the wireframe + animation interconnection subsection. The integrated group (M = 22.13, SD = 9.60) performed significantly better than the isolated group (M = 11.59, SD = 10.74) for all three subscores combined.

An Independent samples paired-test, equal variances not assumed, (t = -1.842, df = 30, p > .05) demonstrated there were *not* significant differences among the groups for the subcomponent diagram labeling questions.

Overall, the diagram labeling section demonstrated strong significant gains learning for the integrated group, suggesting students in this group formed a strong spatial model of this complex system, where the effect size of gains was patterned after the spatially complexity of the sub-components and interactions the three question types required.

Table 18: Free Recall Diagram Labeling Subcomponent Granular Results

DIAGRAM LABELING SUBCOMPONENT QUESTIONS GRANULAR ANALYSIS:

Condition	Q2 : Label Na+/K+ Ions : AP	**Q4 : Label Ca+ Ions Into Soma	**Ion-Based Questions (Q2 + Q4, throw out Q3)	Q3 : Label where Na+ enters (redund.)	Q5 : Label NT's	Section Overall
Isolated Visuals	M=1.07/2 SD = .76	L = 12/17 H = 5/17	M=1.17/3 SD = 1.20	L = 11/17 H = 6/17	M=1.5/2 SD = .855	M=2.76/9 SD = 2.42
Integrated Visuals	M=1.56/2 SD = .49	L = 4/15 H = 11/15	M=2.1/3 SD = 1.04	L = 9/15 H = 6/15	M=1.77/2 SD = .60	M=4.23/9 SD = 2.04
	t = -2.04 df = 25 p = .05 Coh. D = .80	X_2 = 6.15 df = 1 p < .02 PearsR=.44	t = -2.314 df = 30 p < .03 Coh. D = .85	X_2 = 1.95 df = 1 p > .05	t = -.941 df = 25 p > .05	t = -1.842 df = 30 p = .075 > .05

Note: Means are presented in the format "Mean Score for DV"/"Total Possible Points for DV"

*Also, please note Q1, involved only mental animation steps, and no subcomponent steps, hence is excluded from this analysis

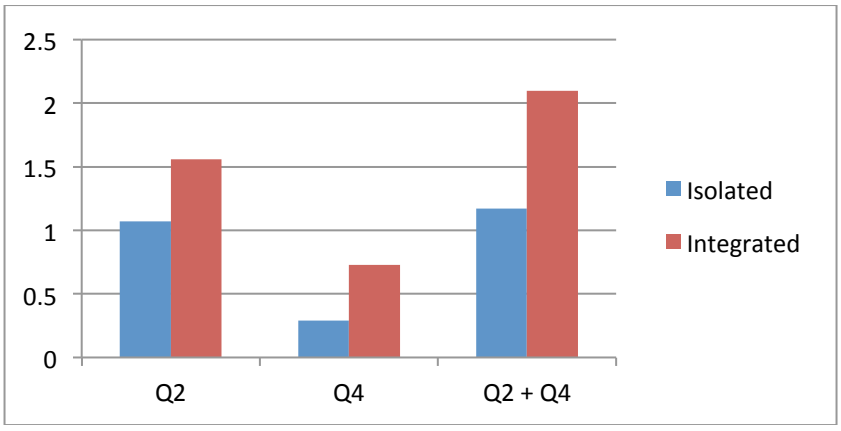


Figure 71: Ion-Based Questions Categorical and Continuous Scores Graph

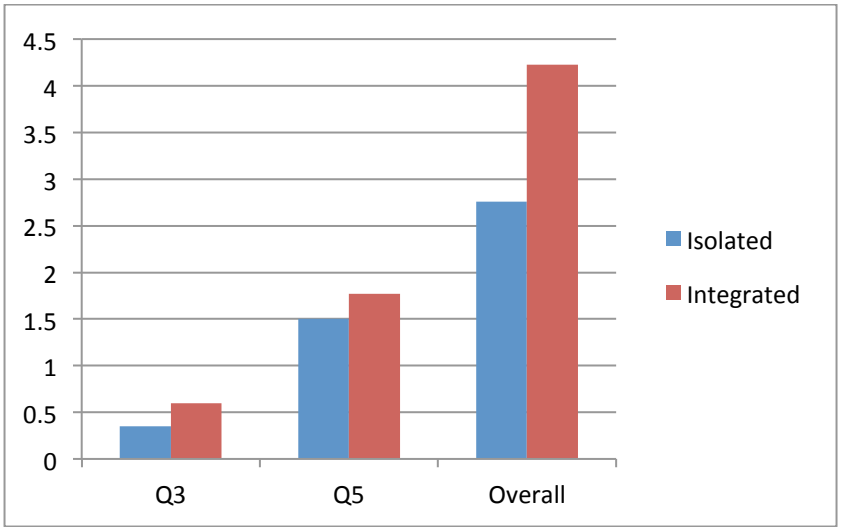


Figure 72: Questions 3 & 5 Categorical and Continuous Scores Graph, 140

Examining the subcomponent diagram labeling question more closely, an independent samples paired-test, equal variances assumed, demonstrated there were significant differences among the groups for the second diagram labeling question subcomponent sub-score (t = -2.04, df = 25, p = .05, Cohen's D = .80), the fourth diagram labeling question subcomponent sub-score ($X2$ = 6.15, df = 1, p < .02, PearsR=.44) and the combined Ion-based diagram labeling question subcomponent sub-score (consisting of Q2 and Q4), (t = -2.314, df = 30, p < .03, Coh. D = .85).

Specifically, the integrated group (M = 1.56, SD = .49) performed significantly better than the isolated group (M = 1.07, SD = .76) for the second diagram labeling question subcomponent sub-score. The integrated group (H = 11/15, L = 4/15) performed significantly better than the isolated group for both the fourth diagram labeling question subcomponent sub-score (H = 5/17, L = 12/17) and the combined Ion-based diagram labeling question (Integrated: M = 2.1, SD = 1.04; Isolated M = 1.17, SD = 1.20).

The third diagram labeling question subcomponent sub-score did not demonstrate significant differences among groups ($X2$ = 1.95, df = 1, p > .05), nor did the fifth diagram labeling question subcomponent sub-score, (t = -.941, df = 25, p > 05), or, again, the diagram labeling question subcomponent sub-score section overall (t = -1.512, df = 25, p > .05). Please note that questions 3 and 4 were originally scored on a continuous scale from 0-2, but then converted to categorical scale to maintain consistently overall, where any score below 1 received a 0, and any score from 1-2, received a score of 1.

Overall, dissecting the diagram labeling question subcomponent sub-score section demonstrates significant differences in some relevant ion-based questions for this section, providing some evidence that the integrated group chunked the movement of ions in the lesson

more effectively, which led to increased spatial retention of the locations of ions presented to both groups equivalently in the lesson in the neuron.

Discussion

Before analyzing the results, let's return to the main original hypothesis:

H. Students shown detailed, integrated cellular animated videos of the major subcomponents in the neuron will perform significantly better on free response questions and diagram questions than students shown less detailed, isolated videos.

Specifically, here both the integrated and isolated groups view stop frame animated videos. Both groups will view wireframe diagrams of the neuron, but only the isolated group will have the locations of these subcomponents pointed out repeatedly on the wireframe throughout treatment before they view the corresponding animations.

The theoretical reasoning behind this is the conjecture that information elaborated by depicting detailed interconnections among concepts, a higher central executive modulated attentional *external* cognitive load in long term working memory, is retained better than information that is elaborated by depicting interconnections with less details. The mechanism behind this is that by chunking information more effectively, though elaborations on conceptual material, spatially powerful, attentionally efficient mental models for this material are formed which take a lower *internal* and *sum (ext + int)* attentional cognitive load to retain and recall than the core material presented in isolation and encoded in more isolated, less chunked mental models. The major evidence supporting this directly is from the free essay response and diagram labeling subcomponent subscore data for the information presented equivalently to each condition, in conjunction with the cellular interconnection data for other sections which provide some initial support for chunking as the mechanism by which the subcomponent data was recalled more effectively in the integrated animation group.

Evidence for greater learning of subcomponent neuron sub-component concepts

The subcomponent subscore for the free recall essay reached significance for the continuous, but not the categorical subscore. This is likely because the continuous subscore by definition is more sensitive at detecting differences between groups. While the categorical subscore demonstrated both groups recalled the main idea for the subcomponent neuron subcomponent concepts equally, the integrated group recalled many more details as this group better chunked the information. Perhaps both groups did not differ significantly on the categorical score because students received a binary point (1/0) for displaying any knowledge related to the concept being evaluated and hence, this categorical scale may not have actually detected whether students actually knew the main idea underpinning each concept or not. This would explain why neither group differed significantly on this subscore, because displaying any knowledge of any detail related to the core subcomponent concepts was an easy task for either group to perform. The Cohen's D for this gain is .84, which provides strong evidence that the integrated group performed better at recalling the details of the subcomponent subcomponents in the neuroscience lesson.

While the subcomponent subscore for the diagram labeling section did not reach significance overall, a more granular analysis reveals that the major ion-based questions did have significant gains in learning for the integrated group over the control. Let's evaluate each of the four subcomponent questions in this section for applicability to this more granular analysis. The concept of neurotransmitters binding and release were the first and last concepts in the lessons for both groups. Hence strong recency and primacy effects may explain why both groups performed well on this question (5). Question 3 deals with labeling sodium ions, specifically where they enter the neuron, but is not as mentally taxing as Q2, which requires subjects to label

both where sodium enters and potassium exits the neuron, however Question 3 did have a large proportion of low scores in both the isolated and integrated group which proffers evidence against the assertion that this question was too easy. But, Question 3 is also redundant, as Question 2 already deals with sodium entering the neuron. Taking questions 3 and 5 out of the analysis, the sodium and potassium subcomponent ion based labeling questions (Q2), and calcium ion subcomponent labeling question both demonstrated significant increases in learning for the integrated group over the control, as did the combined score for both of these questions, the combined "ion-based" diagram labeling subcomponent sub-score. The Cohen's D for the combined ion-based question combination was .85, which provides strong evidence for the weight of this finding in proving the hypothesis that the integrated group recalled the subcomponent material more effectively. Overall, this proffers some additional evidence that the integrated group recalled the subcomponent material, as postulated because this group chunked information more effectively, which led to increased spatial retention of the locations of where the ions presented to both groups equivalently in the lesson, entered the neuron.

Hence, examining the subcomponent data across all dependent variables, there was significant gains in learning for the integrated group for the free recall essay continuous sections, as well as the ion-based subcomponent subscore for the diagram labeling section. The Cohen's D for these sections ranged from .74-.84, providing strong evidence for the weight of these findings to support the main hypothesis. Now let's examine evidence that chunking is the driving force behind these gains in learning for the subcomponent concepts by the integrated group.

Evidence for chunking as mechanism for better recall of subcomponent concepts

There is strong evidence from the free recall essay, short answer, What-If and diagram labeling cellular interconnection subscores that the integrated group learned the detailed interconnection concepts greater than the isolated group. This provides a starting point for asserting that chunking is the mediating variable driving the greater gains in subcomponent scores.

Specifically, the free response essay cellular interconnection continuous and categorical subscores were significantly better for the integrated group with large effect sizes (2.54, 2.09) and the short answer detailed and continuous detailed and less detailed subscores for the cellular interconnection questions were significantly better for the integrated group also with large effect sizes (1.72-2.47). This demonstrates the integrated group successfully recalled the cellular interconnection concepts vastly better than the control group. The short answer cellular less detailed interconnection subscores also demonstrate that less detailed verbal descriptions of interconnections among sub-parts given to the control group was not enough to recall these interconnections effectively absent the detailed verbal and visual images used to depict these interconnections that was given to the integrated group.

The What-If section also demonstrated large gains in learning with large effect sizes (1.39,1.49), for the cellular interconnection subscores. This demonstrates the cellular interconnection concepts were helpful in assisting the integrated group in problem solving situations that require performing spatial/conceptual transformations on cohesively chunked mental models of the neuroscience signal transmission system over the control group. Last the diagram labeling cellular interconnection type subscores (wireframe and mental animations) were significantly better in favor of the integrated group, with large effect sizes from 1.07-2.28,

suggesting that better recall of the interconnection concepts led to mental models for the integrated group that encoded better the spatial movements of ions and neurotransmitters in the lesson versus the control group.

Overall, there is much evidence demonstrating that the additional external cognitive load of being presented with additional details about the interconnections between neural subcomponents did not overload the integrated group, and in fact this group recalled the neural subcomponents concepts better than the isolated group while also retaining these detailed interconnection concepts as well. This is an important step in proving that chunking the subcomponent and interconnection concepts is the mechanism by which the integrated group learned the neural subcomponent concepts better than the isolated group. In future analyses, a path analysis should be done among the seven subcomponent concepts, which may optimistically demonstrate significant differences in chunking the subcomponent concepts in favor of the integrated group.

The evidence that the integrated group better recalled the subcomponent concepts, in conjunction with the evidence that the integrated group better recalled the interconnection concepts provides some initial evidence that chunking both these subsets of concepts is the cognitive mechanism driving the gains in recall for the subcomponent concepts. Future analyses using a path analysis approach will likely show significant differences in chunking the subcomponent concepts favoring the integrated group. Also, in the future a path analysis of the independent, dependent and mediating chunking variables will be conducted to better ascertain the validity of the various connections in the cognitive causal model.

Hence, framed in terms of the Virk LTWM Multimedia Framework, the additional interconnection verbal and visual material in the integrated lesson raised the external attentional,

central executive modulated cognitive load of processing the presentation in long term working memory versus the control, but resulted in tight, cohesive mental models of the neural signal transmission lesson which had a much smaller internal attentional cognitive load for retention and recall. The overall attentional cognitive load of processing the neural signal transmission lesson, external + internal, in long term working memory was therefore much smaller than the cognitive load, external + internal, for the control group, and hence the integrated condition recalled more core concepts presented to both groups as well as more detailed elaborations on these concepts presented just to the integrated condition. This advocates the instructional practice of presenting subcomponents of a complex domain as an integrated whole where the interconnections among subcomponents are depicted with great detail.

CHAPTER V

CONCLUSION

Theoretical Contributions

This study was the first to apply the Cowan Long Term Working Memory framework to the cognition of neuroscience teaching, and one of the first to apply the framework to STEM education cognition. More generally, this study was the firs to apply the Cowan framework to learning from animations in to the cognitive process of chunking, an extremely important process for learning complex STEM systems. Specifically, how students process a complex neuroscience/STEM system which has many subcomponents interacting with one another, was therefore framed in terms of what subcomponents and interconnections between subcomponents would reach the foci of attention, long term working memory, or be outside the realm of central executory modulated attentional processes for isolated versus integrated external representations. Under the updated Virk Cowan Long Term Working Memory Model, neuroscience/STEM cognition was analyzed in terms of gustatory, somatosensory and olfactory modalities in addition to visual and verbal ones and the Cowan model was incisively compared to the Baddeley model, noting the key differences and similarities.

Cognitive load theory, traditionally not viewed in terms of grades of attention, was also framed using the Cowan framework through this study, where higher cognitive load activities and representations required higher levels of attentional activation than lower cognitive load activities and representations. Cognitive load theory also traditionally does not account for the internal load of chunking, and this dissertation emphasized a cognitive load framework which takes into account the sum external load of presentation and internal load of processing the

presentation, especially chunking processes, instead of simply the external load of presentation. This creates a more precise and accurate model of cognitive load, which does not necessarily dictate that the more external stimuli a presentation has, the greater cognitive load of processing. Last, in terms of the literature on part-whole learning, this study is one of the first to incisively attack the construct of knowledge integration, where subparts of a domain can be duplicated and assembled to create a cohesive whole, as previous studies on part-whole learning, emphasize parts of lists or parts that comprise a narrative only. Importantly, this is the first study to directly study how visual knowledge integration occurs in a complex STEM domain.

Practical Implications

The results of this study proffer evidence that visually integrating the subparts of a complex STEM domain, here neuroscience, will result in retention of many of the interconnections between subparts presents as well as the subcomponents themselves versus isolated visual presentations of the subparts of a complex STEM domain. Hence, students not only learn the subparts of the STEM domain better, but also have a richer understanding of how these subparts interact with each other to create the whole system, a vitally important skill to foster deep spatial comprehension of STEM.

As stated in the introduction, this method of visually integrating the sub-components that comprise a domain is a generally applicable instructional methodology for lower the sum attentional cognitive load and enhancing cohesive mental model formation for any spatially complex domain that has many sub-components that interact with each other in spatially complex ways to a high degree. This includes but is not limited to Biology, Physics, Chemistry, Calculus Statistics, Accounting, Financial Trading Processes, Data Visualization Interfaces,

Computer Science and even aspects of law, language learning and other domains.

More specifically, in physics, the coulomb's force of attraction between electrons, causes kinetic energy of movement which is current in a wire, which creates magnetic fields. These three concepts, Coulomb's force, current and magnetic fields should therefore be visualized and taught together in a layered, integrated circuit simulation for maximal retention and spatial understanding of the circuit complex system. This circuit system can even be combined with a capacitor to integrate these domains together, as many concepts such as electrostatics, electric field strength and current overlap between these domains. Kinematics can even be integrated into these integrative units, as electrons can serve as a foundation for learning about velocity, acceleration, angular momentum and other science concepts.

In Chemistry, the enthalpy of formation of molecular bonds, valence electrons which create these bonds, L'Chatelier's principle of how bond formation/dissociation drives reactions to create molecular bonds, phase changes and many other topics such as stoichiometry, equilibrium and entropy can all be visualized, integrated, and taught together in a chemical molecular simulation system.

In computer science, students should be instructed to use and explore completed computer programs, such as racing games and database driven websites, and to see how the code underpins the various functions of these computer programs and how all the various functions work together in the complete program, instead of learning piecemeal functions without seeing the completed program until the end of the curriculum.

Overall, in order to begin the arduous, yet critical task of visualizing and integrating causally related concepts in STEM, and also other domains, subject matter experts for each area will have to work with instructional scientists and programmers and animators to create visually

interactive, integrated learning programs, such as Ipad and tablet apps (see vCapacitor and iGasLaw in Itunes, 2012). It is only through this team trifecta effort that these modules will be created scientifically accurately, maximizing use of cognitive learning principles, and properly using the latest visual animation and computer technologies.

Granted, this effort will require a substantial amount of money from granting and industrial sources and time, but hopefully since these modules are digital, they can be widely used across schools in America and updated and combined as needed. Teacher training in the use of integrative learning apps for STEM and the cognition behind integrative methods will be critical. Whether teachers and schools accept/resist integrative apps into their curriculum to various degrees will be a major question of interest to their success. New kinds of assessments will be needed to better understand how integrative learning modules foster deep, malleable spatial representations of STEM domains, and student performance on common standardized science assessments, such as the Regents, SAT II and AP Biology, Chemistry, and Physics exams will have to be carefully evaluated as well.

Limitations

The major limitation of this study in terms of experimental design is that some science educators may argue that some aspects of the elaborative interconnections among subcomponent concepts were sometimes part of the subcomponents themselves and argue against the equivalency of certain concepts between the control and experimental conditions. Granted, a biology science education professor at Teachers College did approve of the equivalency of all concepts in the study, but there is still room for interpretation. For example, one could argue the bottom action potential channels were not part of the elaboration of the top channel, but rather another version of it, and argue against the equivalency of presenting the action potential concept

twice across both conditions, stating that the experimental in fact received the action potential channel four times. Similar arguments could be made against the equivalency of the two additional calcium channels in the Soma of the neuron and the additional calcium channel before the synaptic bouton area, and for other neural subcomponent structures. Of course, in this study, we argue that these extra presentation of action potential, calcium, phospholipid, dendrite and other subcomponents structures are part of the elaboration of specific instances of these structures in the neuron. It will be interesting to see as more integrative STEM research studies are performed how various STEM cognition researchers view what information is an elaboration of another instantiation of the core subcomponent, which in many instances is a slippery slope.

Secondly, as the experimental condition received both more visual detail in the interconnections and more verbal detail, it is unclear as to which modality is driving the learning gains in subcomponents, or even the retention of the interconnections for the experimental condition? A new study will have to be performed to tease this apart (please see Future Research section).

Third, looking at the causal diagram below:

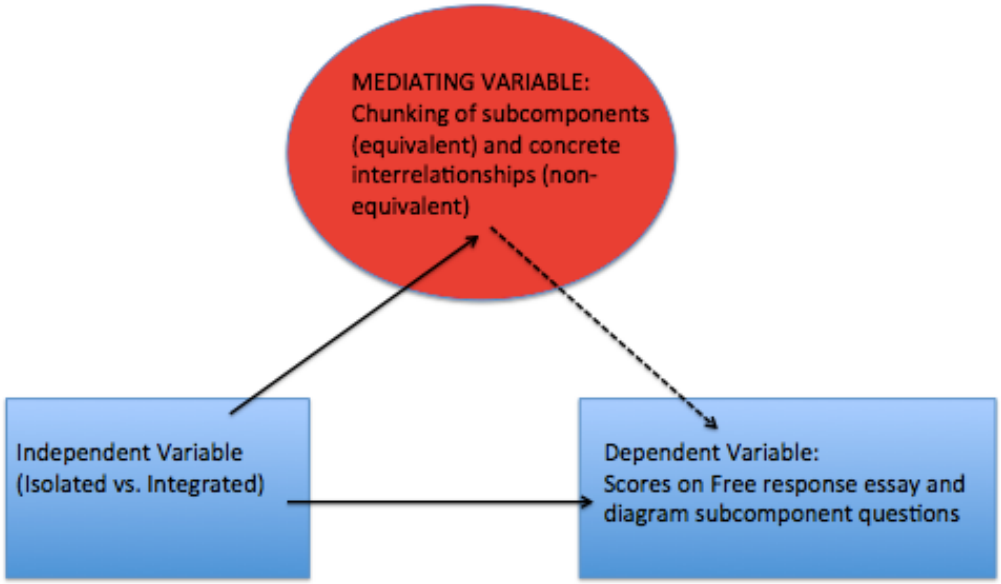


Figure 73: Cognitive Causal Model for Integrative Neuroscience Study

While evidence has been proffered that the experimental group performed better on subcomponent questions and did retain at least half of the elaborative details about interconnections between subcomponents they were presented with, direct evidence that chunking mediated the increased score on the subcomponent dependent variables still needs to be provided in future research, as only indirect evidence has been provided by this dissertation study. Likely a path analysis of the various dependent, independent, and mediating variables in the causal path diagram will have to be analyzed utilized statistical analyses that take into account the conditional probability that if one concept is presented in a student's essay response, the probability that the others will be present.

Fourth, this study was on a substantial amount of neuroscience material, 3-6 lectures worth in an introductory neuroscience course, centered around the action potential, but the impact of visual integration on learning gains should also be studied in a larger neuroscience

curriculum, where 12-25 lectures of neuroscience material are taught through a single visually integrative representation. For example, the various brain areas, pathways, and reflexes, should be studied in a cellular and molecular visual model, using the visually integrated animation in this dissertation study as a foundational unit for each neuron in the model. Learning gains may be more robust the more material is presented integratively versus isolated presentations, but this is unclear from this dissertation study.

Future Research Directions

Assessment

More drawing questions could be explored, which require the student to draw what specific segments of the neuron look like at different points in the action potential, as well as more multiple choice and fill in the blank questions. Additional transfer tasks that could be designed for integrative neuroscience experiments which could be applied to other domains, include more numeric-centered versions of the transfer problems used in this dissertation, such as *"Describe what would happen if the amount of phospholipid was reduced 50% in the area between the first set of Sodium and Potassium channels and second set of Sodium and Potassium channels. What would happen if it was reduced 25%?"* Students could also be asked problem solving questions that involved multiple neurons connected to one another, an inverted a neuron, changing the locations of the front, middle and back of the neuron, and relating neural functioning to electric circuit principles. Students could also be given access to the neuron animations while they answer problems solving questions, to assess the ability of the representation to enhance problem solving in isolation from the student's ability to recall the representation spontaneously.

Experimental Design

In additional to designing and performing cognitive measures of chunking via a path analysis, future studies should be done which use the same verbal transcript based off of the integrative, experimental condition for both conditions, but differ only in the isolated versus integrative animations presented. This will tease apart how much it is the extra verbal details, or visual details, conceivably both, that are driving the increased learning gains for the subcomponents. More efficacy studies on the integrative neuroscience lesson on student comprehension in high school Biology and college neuroscience classes should also be conducted. Standard tests of verbal/visual working memory, spatial ability (paper folding) and attentional capacity (Stroop, etc.) as well more measures of cognitive load such as self-reported measures and direct measures such as pupil dilation, heart rate and fMRI measures, secondary dual task measures of cognitive load should be utilized as covariates in the future studies on integrative STEM visualizations.

Content Domains/Technologies

Future studies can explore the value of adding touch interactivity to the neuroscience animations, such as iPAD, swipe, tap, and drag gestures to open channels, drag ions and and release neurotransmitter. Interaction effects with visually integrated versus visually isolated presentations will also be studied to tease apart which instructional factor is driving learning gains precisely. Also, sliders can be used, to allow students to add subcomponents and then run the neuron action potential model to see how the changes that would occur subsequently. For example, a slider to increase the amount of myelin would speed up signal transmission when the action potential simulation was run:

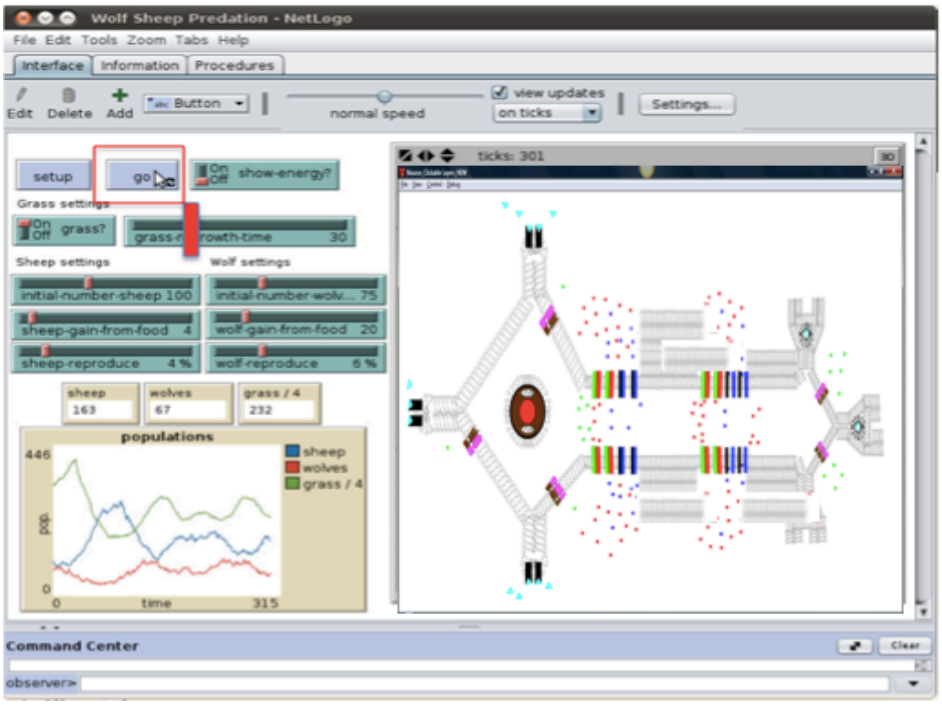
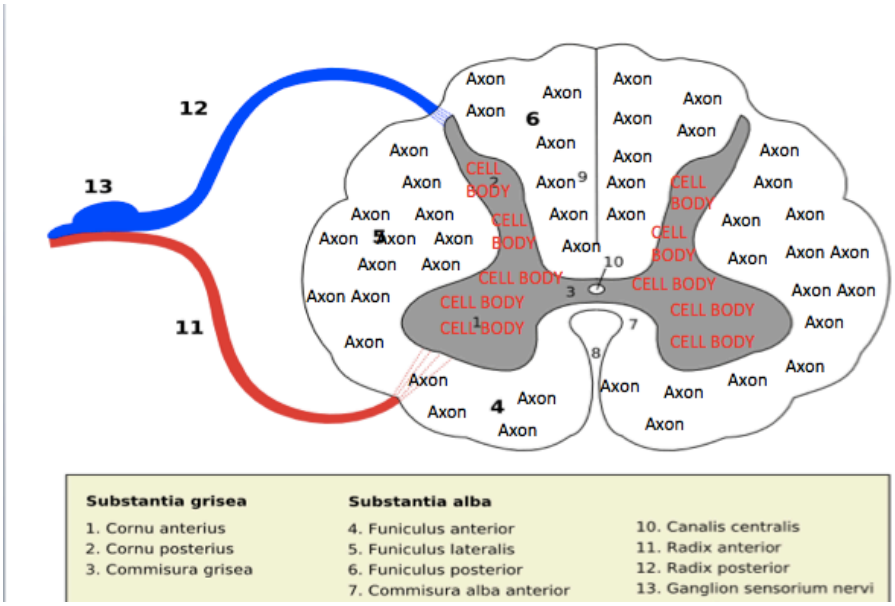


Figure 74: Mockup of Slider Based Neuron Simulation

A 3d model of the Integrated neuron could also be created and studied using programs like Autodesk Maya, and students could also be shown a real neuron, as it looks under a microscope in addition to the schematized neuron used in this study.

In terms of studies with new content, the molecular, layered study from experiment 1 should be updated and run again, controlling for cognitive variables more precisely. The integrative cellular and molecular content could also be expanded to the spinal cord, and depicting the knee jerk reflex in terms of the neural cellular subcomponents and structures (please see below), and eventually the entire nervous system and its connections with other biological systems.



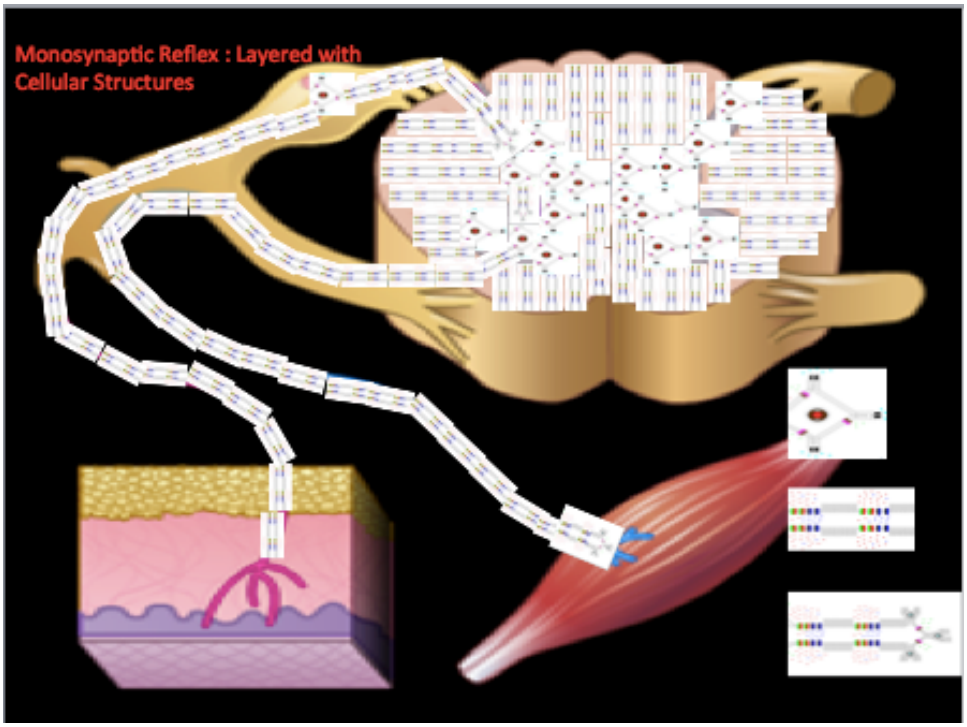


Figure 75: Diagram of Neuron Cell Bodies and Axon, and Integration of Cellular Structures Mockup

Importantly, visually integrative studies should be done in other STEM domains such as chemistry, physics, computer science, mathematics (calculus), statistics and domains outside STEM, such as history, law and English (please see practical implications section). Multiple STEM domains can also be integrated, for example using Biochemistry and Biophysics curriculum, a visually integrated world, where biology, chemistry and physics, and the corresponding mathematics concepts are taught together is conceivable.

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Appendix A: Experiment 1, Control Verbal Transcript

STRUCTURAL-SUPERFICIAL LEVEL OF NEURON

Let's go over the basic structures that comprise a neuron by examining this structural model of the neuron
At the most basic level, the neuron is comprised of 4 basic parts :

1. These projections, called **dendrites**
2. The cell body, and nearby area, called the **soma**
3. A long projection after the cell body, called the **axon**, which contains strongly insulated areas called **myelin sheaths**. The breaks in these sheaths are called **nodes of ranvier**.
4. The end of the neuron after the axon, which contain projections called **synaptic boutons**

*Great, now that you have a basic overview of the neuron we will view the cellular model of the neuron and look at these structures in greater detail and learn how they interact with one another

BASIC CELLULAR OUTLINE OF THE NEURON

**There are 5 major steps that occur when a signal is getting transmitted by a neuron.*
Let's go thru each of these steps and the cellular structures of the neuron.

STEP 1

STRUCTURES :
Throughout the neuron are these structures, which are phospholipids.
Each phospholipid is comprised of a phosphate head and a tail of carbon and hydrogen that extends from this head.
These phospholipids line all the structures of neuron
These neon blue structures are neurotransmitters
These black structures are dendrite receptors.

<play animation>

The first step in the action potential, is that neurotransmitters released from a neuron nearby move towards the dendrite receptor and bind to the dendrite receptor.

STEP 2

STRUCTURES :
These green ions are Calcium ions.
This is a calcium channel, as you can see it has two subunits, a pink and brown one.

<play animation>

- Once the neurotransmitter binds to the dendrite receptor the Calcium channels in the Neuron open up and Calcium ions flow into the neuron

- Then these Calcium channels close

STEP 3

Let's point out some important structures in the axon <move along entire axon> of the neuron :
<point to AP structures>
These are Sodium channels, comprised of green and red subunits
These are Potassium channels, comprised of black and blue subunits
These red dots are Sodium ions
The blue dots are Potassium ions

- The cluster of Calcium ions near the first set of Sodium channels, triggers the Sodium Channels to open, which beings a series of events called the **action potential**.

<start animation>

- This causes Sodium to enter the axon

- After a while the Sodium channels close

- Then Potassium channels open and Potassium ions leave the axon

- As this is occurring, the Sodium ions that previously entered to axon, cluster together and move along the axon

This is the last step in the action potential

STEP 4

< >

The fourth step (not shown here) is that the <action potential> reaches the calcium channels at the end of the axon which triggers them to open

STEP 5

STRUCTURES :

<point to synaptic bouton>

This again, is the synaptic bouton

<point to synaptic vesicles>

Within each bouton are a few of these synaptic vesicles, which are spheres which contain neurotransmitter molecules

<play animation>

- As a result of Calcium channels triggered by the action potential opening, synaptic vesicle with neurotransmitter inside is triggered to move toward to end of the synaptic bouton

- Then the synaptic vesicle opens up, exposing the neurotransmitter and the neurotransmitters that were inside the synaptic vesicles then move thru this opening in the synaptic bouton and out of the neuron entirely

- If a second neuron was nearby these neurotransmitters would bind to the dendrite receptors of this neuron and the entire process we just went thru would repeat again

MOLECULAR NEURAL STRUCTURES

<point to phospholipid>

This is the phospholipid that surrounds the neuron membrane at the molecular level

Here, the phosphate head is in pink

Emanating from the phosphate head is a series of carbon and hydrogen groups connected to one another, the **hydrocarbon tail**

As you can see there are two phosphate heads, which have hydrocarbon tails which are touching each other, and are symmetric to one another

<next molecular slide ; point to acetylcholine>

This is was a neurotransmitter, which is an acetylcholine molecule in this example looks like at the molecular level.

Note that the acetylcholine molecule has two oxygen molecules at one end, and a nitrogen molecule at the other end

<protein receptor>

Receptors and channels in the neuron are made up of protein molecules, like this molecule here.

Protein molecules are comprised of the following repeating subunit

<point to nitrogen and R group>

A nitrogen molecule attached to a carbon molecule attached to an “R” Group

An “R” group is a set of various molecules all linked to each other

For example, a series of Sulfate molecules linked together

Importantly, different protein molecules have different “R” groups, denoted by different colors throughout this animation, which gives each protein molecule different shapes and properties

<point to carbonyl group>

The “R” group is then attached to a carbon with an oxygen molecule and then this subunit repeats

<Na+ Ion>

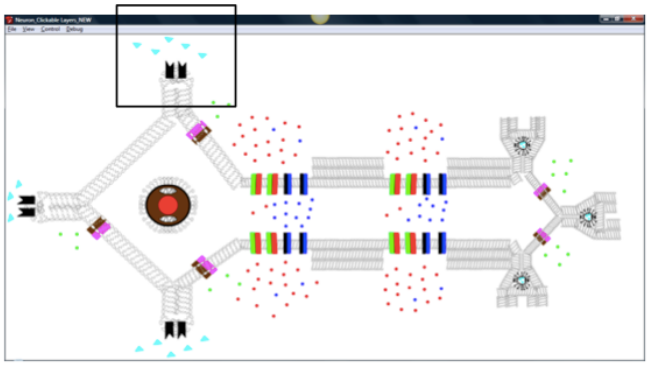
Here is what the ions in the neuron model look like at the cellular level.

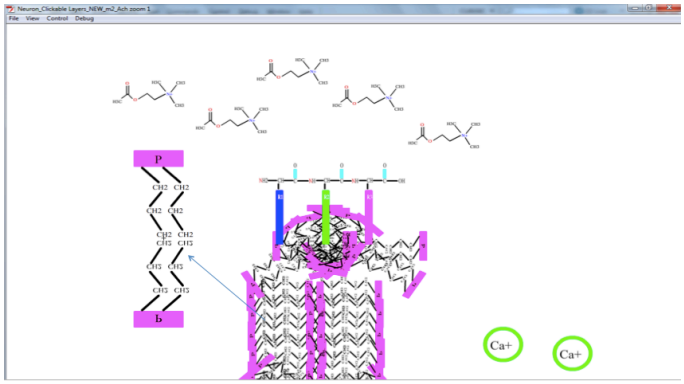
Here, we see what the red Sodium ion looks like at that molecular level

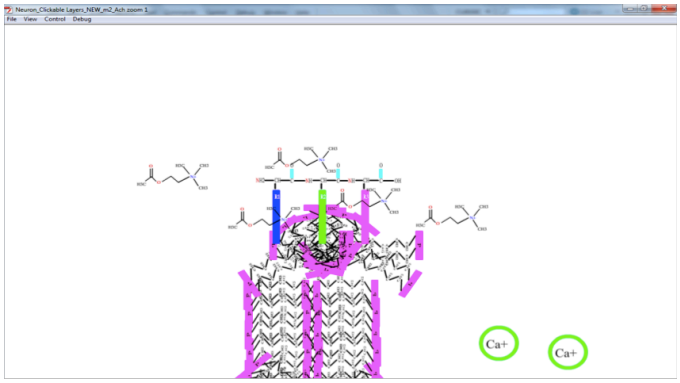
which have one positive charge each

Appendix B: Experiment 1, Experimental Condition Molecular Animations Screenshots

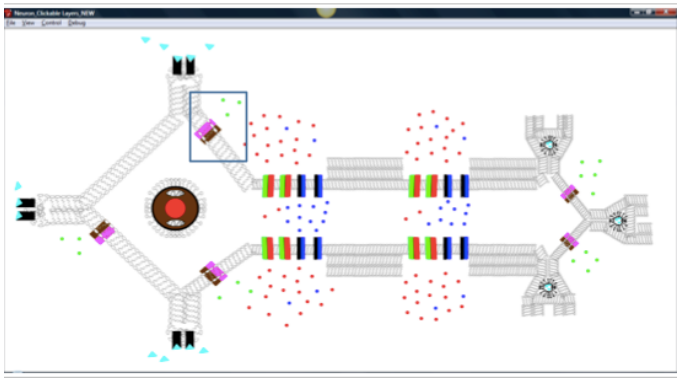
1. Neurotransmitter Binding to Dendrite

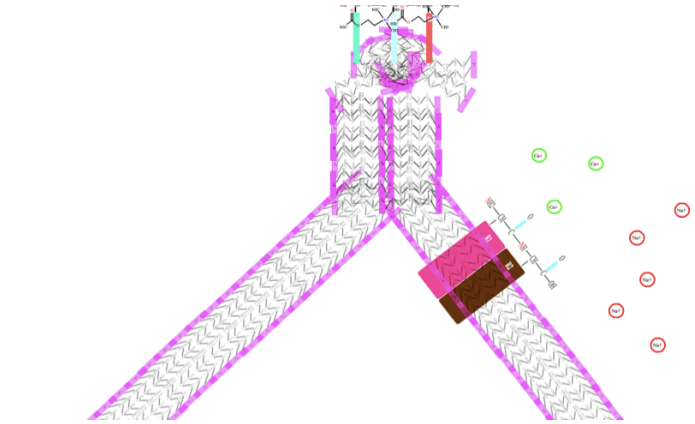


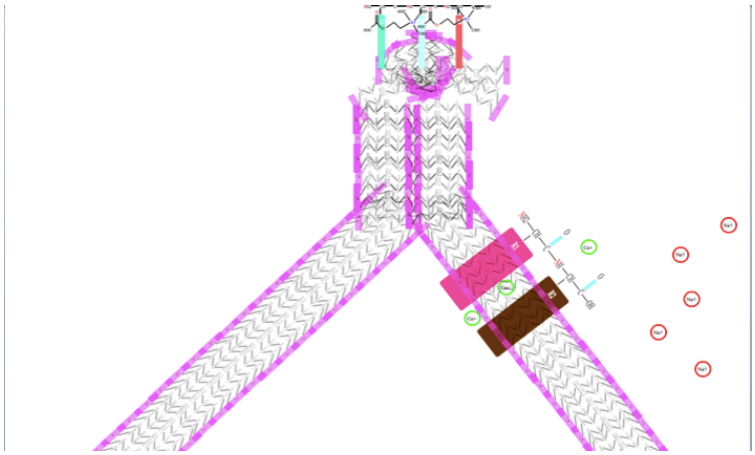


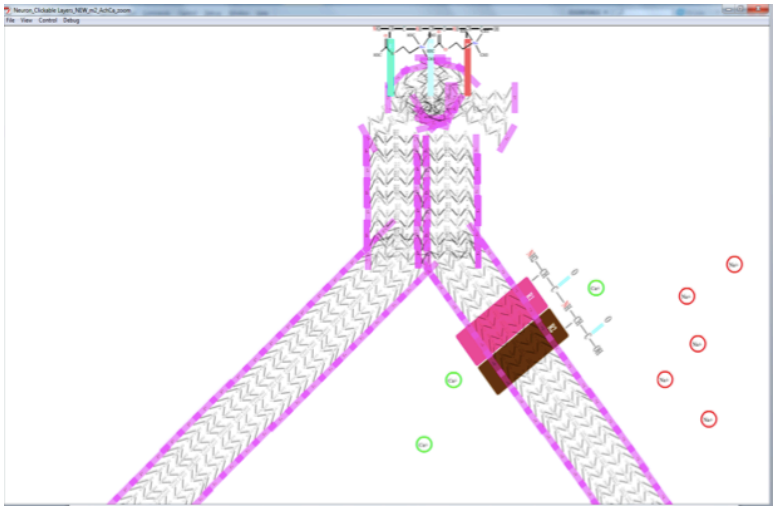


2. Calcium Channels Opening at Dendrites

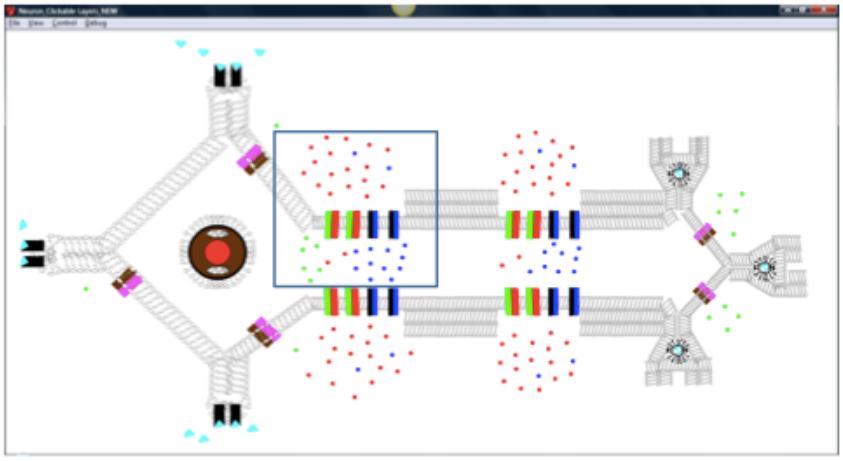


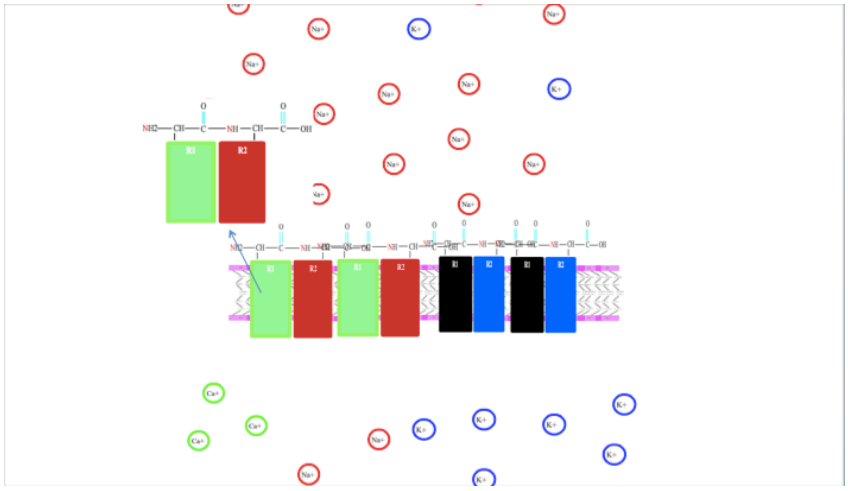


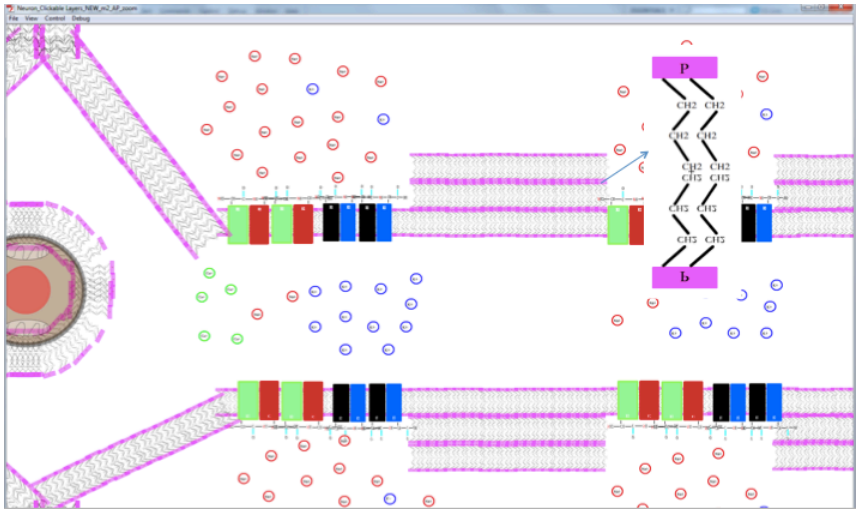




3. Action Potential



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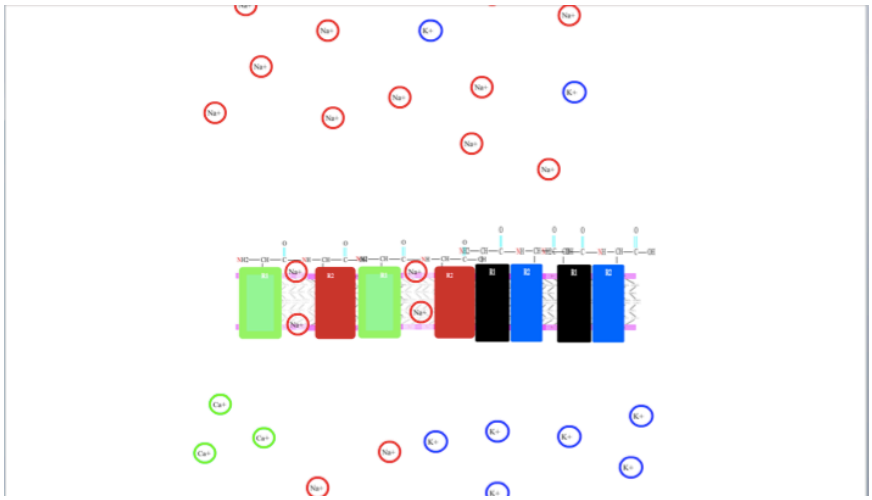
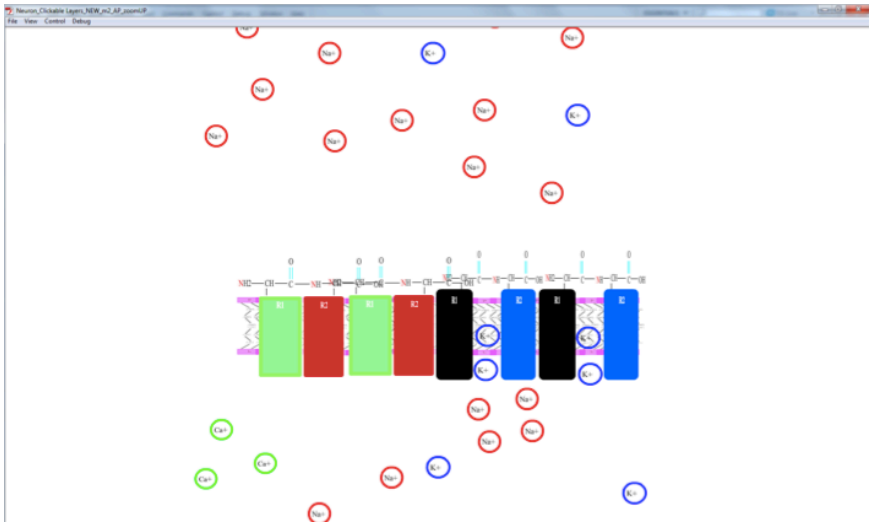
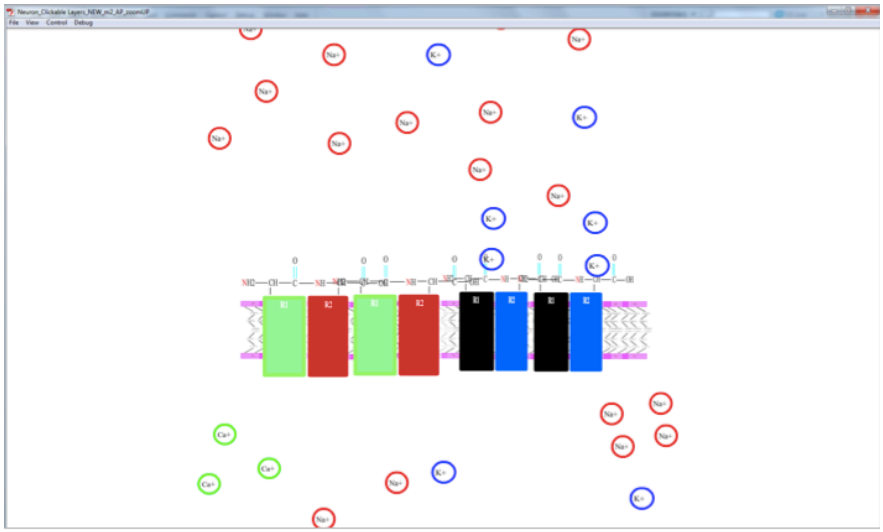
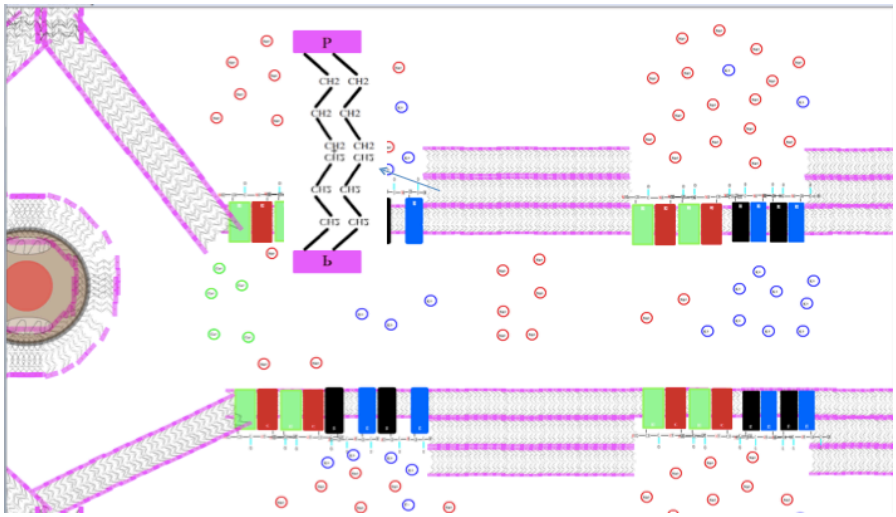
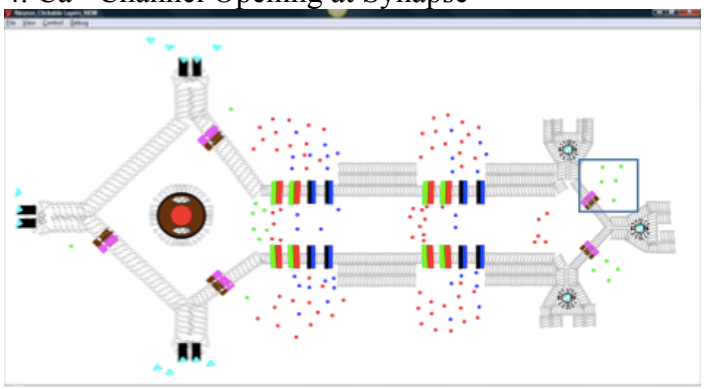


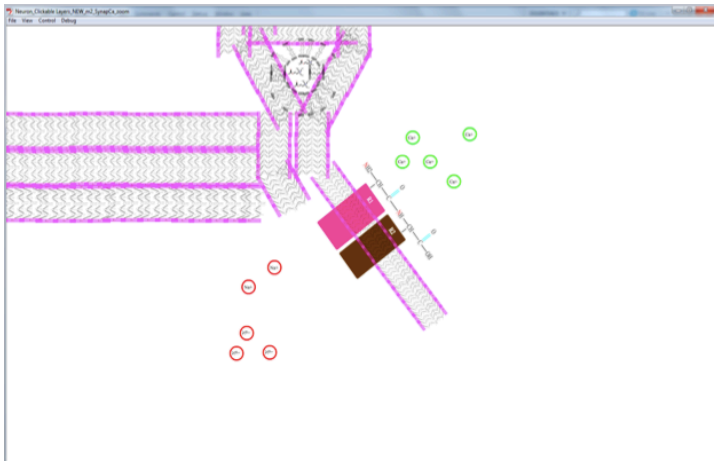


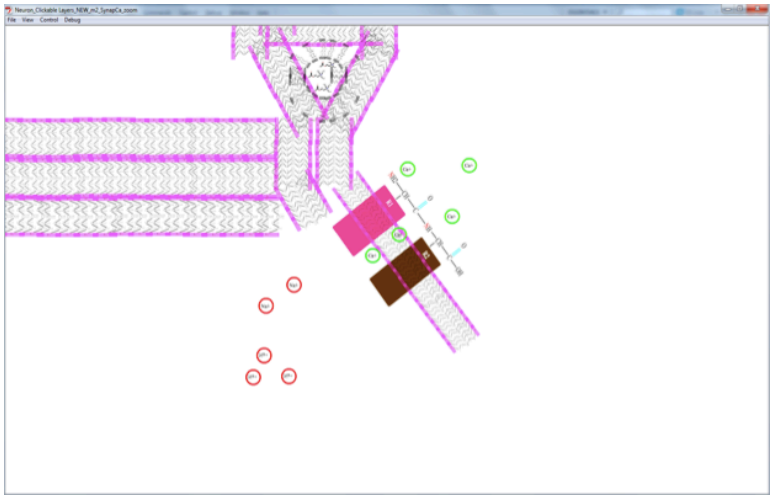


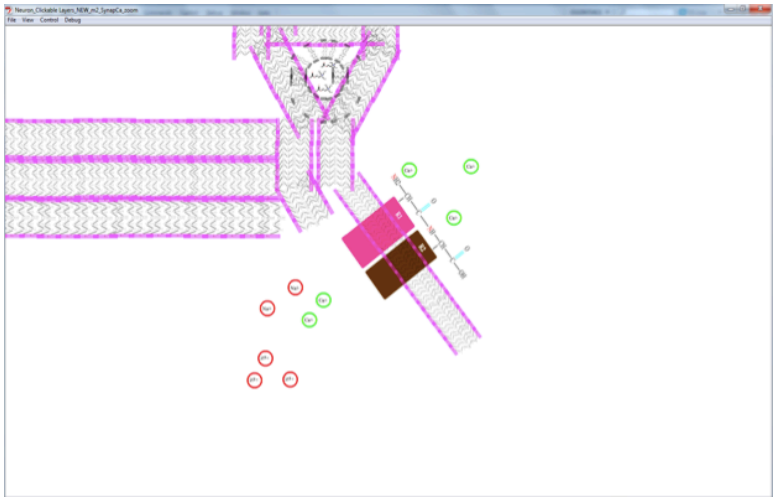


4. Ca+ Channel Opening at Synapse

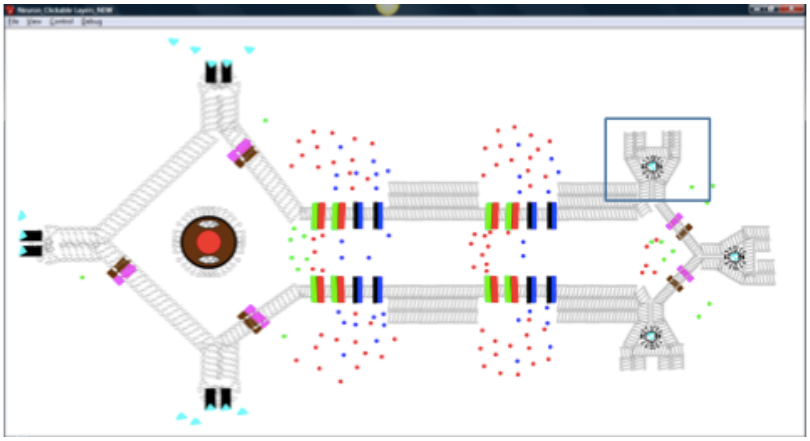


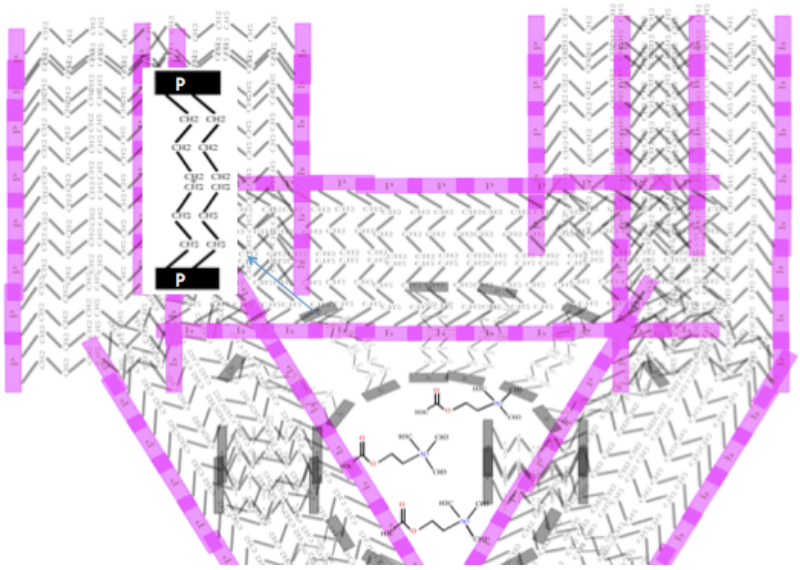


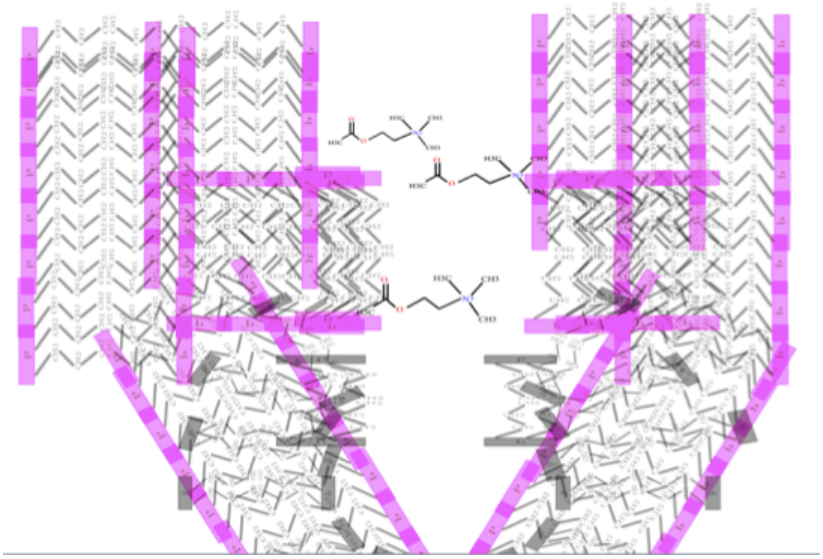




5. Neurotransmitter Release at Synapse




P
P



Appendix C: Experiment 1, Experimental Verbal Transcript

STRUCTURAL-SUPERFICIAL LEVEL OF NEURON

Let's go over the basic structures that comprise a neuron by examining this structural model of the neuron
At the most basic level, the neuron is comprised of 4 basic parts :

1. These projections, called **dendrites**
2. The cell body, and nearby area, called the **soma**
3. A long projection after the cell body, called the **axon**, which contains strongly insulated areas called **myelin sheaths**. The breaks in these sheaths are called **nodes of ranvier**.
4. The end of the neuron after the axon, which contain projections called **synaptic boutons**

*Great, now that you have a basic overview of the neuron we will view the cellular model of the neuron and look at these structures in greater detail and learn how they interact with one another

BASIC CELLULAR OUTLINE OF THE NEURON

**There are 5 major steps that occur when a signal is getting transmitted by a neuron.*
Let's go thru each of these steps and the cellular structures of the neuron.

STEP 1

STRUCTURES :

Throughout the neuron are these structures, which are phospholipids.

Each phospholipid is comprised of a phosphate head and a tail of carbon and hydrogen that extends from this head.

As you can see these phospholipids form a membrane which surround the neuron
<circle along entire neuron>

The phospholipids also make an internal membrane along the nucleus of the neuron

We aren't going to explore the nucleus in any great detail, but basically the nucleus is a cellular structure which powers the neuron and coordinates the neuron's activities through various messengers

These neon blue structures are neurotransmitters

These black structures are dendrite receptors.

<play animation>

The first step in the action potential, is that neurotransmitters released from a neuron nearby move towards the dendrite receptor and bind to the dendrite receptor.

STEP 2

STRUCTURES :

These green ions are Calcium ions.

This is a calcium channel, as you can see it has two subunits, a pink and brown one.

<play animation>

- Once the neurotransmitter binds to the dendrite receptor the Calcium channels in the Neuron open up and Calcium ions flow into the neuron
- Then these Calcium channels close
- The ions from all the Calcium channels in the dendrite area <point to all 3 channel areas> come together and cluster near the beginning of the axon (point out axon)

STEP 3

Let's point out some important structures in the axon <move along entire axon> of the neuron :

<point to myelin sheath>

These areas where there are multiple levels of phospholipids make up the myelin sheath

Since these areas are so heavily packed with layers of phospholipids, ions are heavily insulated from leaving the axon, this will be important later

These areas where there is no myelin sheath are called nodes of ranvier. Since there are no densely packed phospholipids here, only a single layer, there is space for ion channels :

<point to AP structures>
These are Sodium channels, comprised of green and red subunits
These are Potassium channels, comprised of black and blue subunits
These red dots are Sodium ions
The blue dots are Potassium ions

- The cluster of Calcium ions near the first set of Sodium channels, triggers the Sodium Channels to open, which beings a series of events called the **action potential**.

<start animation>

- This causes Sodium to enter the axon
- After a while the Sodium channels close
- Then Potassium channels open and Potassium ions leave the axon
- As this is occurring, the Sodium ions that previously entered to axon, cluster together and move along the axon

This is the last step in the action potential

- See how these sodium ions can easily pass from one set of Sodium and Potassium channels to the next, thru the heavily insulated area called the myelin sheath ?

Since its so insulated, we don't have worry about any Sodium ions leaking out of the axon

- Then the cluster of Sodium Ions reach the next set of Sodium and Potassium channels and the action potential now repeats.
- The cluster of Sodium ions activates the next set of Sodium channels to open and Sodium ions flow into this part of the axon
- Again, the Sodium channels close after a while
- Then Potassium channels open and Potassium ions inside the axon leave the axon thru this channel
- As this is occurring again Sodium ions cluster and move along the axon towards the end of the axon and the synaptic boutons.

STEP 4

STRUCTURES :

<play animation>

- The cluster of Sodium ions reaches the Calcium channels at the end of the axon
- This triggers the Calcium channels to open and Calcium ions flow into the neuron
- Then these Calcium channels close

STEP 5

STRUCTURES :

<point to synaptic bouton>
Each synaptic bouton is covered in phospholipids
<point to synaptic vesicles>
Within each bouton are a few of these synaptic vesicles, which are spheres made of phopspholipids that contain neurotransmitter molecules

<play animation>

- The cluster of Calcium ions at the end of the axon triggers the synaptic vesicle with neurotransmitter inside to move toward to end of the synaptic bouton

- Then the synaptic vesicle opens up, exposing the neurotransmitter and the phospholipids that comprise the synaptic vesicle merge into the phospholipids of the synaptic bouton

- The neurotransmitters that were inside the synaptic vesicles then move thru this opening in the synaptic bouton and out of the neuron entirely

- If a second neuron was nearby these neurotransmitters would bind to the dendrite receptors of this neuron and the entire process we just went thru would repeat again

BASIC MOLECULAR OUTLINE OF THE NEURON

[Read the section to be recorded a few times before actually speaking it]

Now we're going to see what each of the major parts and steps of signal transmission in the neuron look like at the molecular level, since this requires us to zoom in on the neuron, we're going to have to look at each of the major areas of the neuron at the molecular level individually

STEP 1 :

<point to dendrite receptor area of cellular model>

Let's look at the neurotransmitter binding to the dendrite receptors at the molecular level :

STRUCTURES :

<point to cellular phospholipid>

Let's see what the phospholipid looks like at the molecular level.

<switch to molecular slide>

<point to phospholipid>

First, notice the structure of the phospholipid

Here, the phosphate head is in pink

Emanating from the phosphate head is a series of carbon and hydrogen groups connected to one another, the **hydrocarbon tail**

As you can see there are two phosphate heads, which have hydrocarbon tails which are touching each other, and are symmetric to one another

This is the basic molecular unit of the phospholipid membrane that surrounds the neuron

<back to cellular slide ; point to Acetylcholine>

Let's see what the neurotransmitters looks like at the molecular level.

<next molecular slide ; point to acetylcholine>

Notice the structure of the neurotransmitter, which is an acetylcholine molecule in this example.

Note that the acetylcholine molecule has two oxygen molecules at one end, and a nitrogen molecule at the other end

<back to cellular slide ; point to dendrite receptor>

Let's see what the dendrite receptor looks like at the molecular level.

<next molecular slide ; point to dendrite receptor>

Notice the structure of the dendrite receptor, which is a protein molecule.

Protein molecules are comprised of the following repeating subunit

<point to nitrogen and R group>

A nitrogen molecule attached to a carbon molecule attached to an "R" Group

An "R" group is a set of various molecules all linked to each other

For example, a series of Sulfate molecules linked together

Importantly, different protein molecules have different “R” groups, denoted by different colors throughout this animation, which gives each protein molecule different shapes and properties

<point to carbonyl group>

The “R” group is then attached to a carbon with an oxygen molecule and then this subunit repeats

<play animation>

In this animation we see again the acetylcholine neurotransmitter molecules binding to the dendrite receptor protein

STEP 2 :

<Cellular slide ; point to Calcium Ions>

Let’s see what the calcium ions and channels looks like at the molecular level.

<next molecular slide ; point to calcium ions, point to calcium channel>

STRUCTURES :

Notice the green Ca+ ions, which have one positive charge each

<go thru slides>

Notice that the Calcium channel is a protein molecule comprised of two large “R” subunits, one pink, and one brown.

Also, notice that the “R” groups are different in color than the dendrite protein receptor you just saw previously. These pink and brown R groups, give the Calcium channel the structure it needs to allow Calcium ions to flow through it.

<go back two slides to previous slide>

This is because, while the Dendrite protein receptor and Calcium protein channel are both proteins, they are two different proteins, with different R groups, which have two different functions in the neuron.

<go back and continue slides>

The “R” subunits move apart when the ions flow through the channel, this is how the channel opens letting the Calcium ions in.

<at last slide>

Notice the pink and brown “R” groups push together when the Calcium channel closes.

STEP 3

<Cellular slide ; point to general area>

Let’s see what the Sodium and Potassium ions and channels and the action potential looks like at the molecular level.

<go to next molecular slide>

<go back to cellular slide>

These Sodium channels here,

<molecular slide>

Are here in the molecular model

<go back to cellular slide>

These Potassium channels here,

<molecular slide>

Are here in the molecular model

<point to ions>

And we also see the calcium ions right before the first set of Sodium channels, and we see Sodium and Potassium Ions

<point to AP structures>

In this molecular model of the action potential, we notice the following :

<point to channels>

The Sodium and Potassium channels are protein channels comprised of <point to closeup> a protein made of two “R” groups, connected to each other by this carbon, oxygen, nitrogen bond which get closer or farther away when the channel is opening or closing.

Notice that the red and green R groups for the sodium channel <point to Sodium ch> are different than the black and blue R groups for the Potassium channel <point to Potassium CH>

And different from the R groups we saw previously for the calcium channel or initial dendrite receptor. Accordingly, because the R groups are different they give the channel different properties and functions. Here the red and green R groups make the Sodium channel allow Sodium ions to flow thru it, while the black and blue R groups allow the Potassium channel to allow Potassium ions to flow through it.

The Sodium and Potassium charges are positive charges

The Sodium and Potassium channels are placed inside the carbon and hydrogen tails of the phospholipids
<point to sheaths>
<move to next myelin sheath slide>

The myelin sheath is comprised of multiple stacks of phospholipids <point to molecular closeup>, and therefore, <shuffle between close up and myelin sheath> multiple stacks of hydrocarbon layers one on top of another

As we watch this animation we see the same events occur as before, but now we see what they look like at the molecular level :
<play animation>

- Again, the cluster of Calcium ions near the first set of Sodium channels, triggers the green and red "R" groups of the Sodium channels to move apart, thereby opening the Sodium channel, which beings a series of events called the **action potential**.

- This causes the positive Sodium to enter the axon

- After a while the Sodium channels close when their red and green "R" groups move together

- Then Potassium channels open when their black and blue "R" groups move apart and positive Potassium ions leave the axon

- As this is occurring, the positive Sodium ions that previously entered cluster and move along the axon

This is the last step in the action potential
<point to ions moving along myelin sheath>
<move to myelin sheath slide>

- Again, we see how these positive Sodium ions can easily pass from one set of Sodium and Potassium channels to the next, thru the heavily insulated myelin sheath.

<point to hydrocarbon>
Under this molecular model we now understand it is the stacks of hydrocarbons layered on top of one another that prevents the Sodium ions from leaking
<point to cluster of Sodium ions and start of next set of channels>

- Then the cluster of positive Sodium Ions reach the next set of Sodium and Potassium protein channels and the action potential now repeats as before.

Step 4
<point to cellular model>
Let's look at the calcium channels opening at the synapse at the molecular level
<molecular slide>

- Again, the cluster of positive Sodium ions reaches the Calcium protein channels at the end of the axon

- This triggers the Calcium protein channels to push their pink and brown "R" groups apart and open and allow positive Calcium ions flow into the neuron

- Then these Calcium channels protein push their pink and brown "R" groups together and close

Step 5
STRUCTURES :
<at cellular slide>
Let's look at synaptic transmission at the bouton at the molecular level.

<point to synaptic bouton, cellular>
<move to molecular slide>
Here we can see the synaptic bouton is made up of many phosphate and hydrocarbon molecules <point to pink phosphate molecules>
<now go back to cellular slide : synaptic vesicle>
Also, we see the synaptic vesicles are made of many phosphate molecules in <point to phosphate molecule> which form a circle around these neurotransmitters
Here, we can see that the neurotransmitter inside of the synaptic vesicle are the same neurotransmitter that initially bound to the dendrites in this example, the acetylcholine molecules that we saw earlier in the animation
<play animation>

- Again, we see how the cluster of positive Calcium ions at the end of the axon triggers the synaptic vesicle with acetylcholine neurotransmitter inside to move toward to end of the synaptic bouton

- Then the synaptic vesicle opens up, exposing the acetylcholine neurotransmitter and the phospholipids with their hydrocarbon tails that make up the synaptic vesicles merge with the phospholipids with their hydrocarbon tails that make up the synaptic bouton

- The acetylcholine neurotransmitters that were inside the synaptic vesicles then move thru this opening in the synaptic bouton and out of the neuron entirely. In this model we can see how the oxygen and nitrogen molecules of the acetylcholine molecule move past the phosphates and hydrocarbons of the synaptic bouton as they pass thru this opening.

- If a second neuron was nearby these acetylcholine neurotransmitters would bind to the dendrite protein receptors of this neuron and the entire process we just went thru would repeat again!

Appendix D (Assessment and Grading rubric)

*Please keep track of how much time you spend overall on this test (time yourself) (you will asked this information at the end)

Part I :

PLEASE COMPLETE THIS QUESTION **FIRST**, ONCE YOU ARE DONE, **YOU MAY NOT GO BACK TO IT**!

Please explain the steps of signal transmission in the neuron drawing upon the instructional materials shown and also any steps not described in the instructional materials that are logically necessary for the process to work and make sense, in the space below on this page and on an additional page if necessary:

Part II :

DIRECTIONS : *VERY IMPORTANT, YOU CANNOT RETURN TO A QUESTION ONCE YOU'VE ANSWERED IT, THE END OF THE TEST GIVES AWAY THE BEGINNING, SO ONCE YOU ANSWER AND QUESTION AND MOVE ON, NEVER WORK ON THE QUESTION AGAIN (THIS APPLIES FOR ALL 17 SHORT ANSWER QUESTIONS BELOW)

Cellular Questions (1-10) :

Please write 1-3 sentences for each of the free response questions below, in the space below each question, using information contained in the cellular learning videos ONLY (not information from the molecular learning videos) trying hard to use terminology from the cellular video modules:

1. Explain why neurotransmitter doesn't leak from synaptic vesicles into the synaptic bouton :

2. Describe what ions are present near the synaptic bouton before it opens :

3. Describe the process of neurotransmitters being released at the synaptic bouton from the first event that occurs with the synaptic vesicle ending with the point where neurotransmitter is released, in terms of cellular structures :

4. Describe the structure present in the axon between one set of Sodium and Potassium channels and a second set of Sodium and Potassium channels, called a myelin sheath, and what function it serves :

5. Describe what triggers the action potential and explicitly describe the process by which this trigger was formed:

6. Describe where and how Sodium ions flow during the action potential :

7. Describe what triggers the action potential at a second set of sodium and potassium ions that are located after a first set of sodium and potassium ions :

8. Describe what affect increasing the number of calcium channels that are opened everytime a neurotransmitter binds to dendrite receptors would have on signal transmission:

9. Describe what would happen if the amount of phospholipid was reduced in the area between the first set of Sodium and Potassium channels and second set of Sodium and Potassium channels :

10. Describe what would happen to signal transmission if the Sodium Channel was blocked :

Molecular Questions (11-17) :

AGAIN, YOU MAY NOT NOW RETURN TO ANSWER ANY OF THE CELLULAR QUESTIONS OR ADD TO THEM, ALSO, ONCE YOU START THE QUESTIONS BELOW, YOU MAY NOT RETURN TO A QUESTION ONCE YOU'VE STARTED TO ANSWER THE NEXT QUESTION

Please write 1-3 sentences for each of the free response questions below, in the space below each question, trying hard to use terminology from the molecular video modules and relevant information from the cellular videos :

11. Describe what the structure present in the axon between one set of Sodium and Potassium channels and a second set of Sodium and Potassium channels, called a myelin sheath, looks like at the molecular level (again, using molecular terminology) :

12. Compare the R-subunits for Sodium vs. Calcium channels and how the differences/similarities between the R-groups effects how each channel functions :

13. Describe how the Sodium channel works at the molecular level :

14. Describe how the action potential works in terms of changes in positive charge that are occurring inside and outside the neuron membrane :

15. What if the R-groups for Sodium channels were switched with the R-groups for Calcium channels, what would happen :

16. What would happen if one of the R-groups for the Potassium channel was deleted :

17. If a neuron was created where the phospholipid has three hydrocarbon tails lined up in a row, instead of just 2, how would this effect signal transmission in the axon, specifically :

SURVEY QUESTIONS (MANDATORY)

PLEASE ANSWER THESE BIOGRAPHICAL QUESTIONS BELOW BEFORE AFTER FINISHING THE EXAM :

Total Time Spent on Test (not including these questions) :

Gender :

Undergraduate Major :

Graduate Major :

Please bold the correct choice below for each of the following multiple choice questions :

1. The last time I took a course that taught concepts about the neuron and action potential was:

   A. Never

   B. High School

   C. College

   D. Graduate School

2. In college and/or graduate school I took the following number of courses that taught concepts related to the neuron and action potential

   A. 1

   B. 2-3

   C. 3-5

   D. More than 5

3. I have taken/am taking a Neuroscience Course of some sort (Example : Brain and Behavior I or II) at TC :

   A. YES

   B. NO

*Once you are finished with this test, please send both 1. This test, 2. Spatial visualization test sheet and 3. Your consent form, to the following e-mail address to get credit for your course with the following title in the e-mail "Neuron Pilot Experiment and <**Your Name, First and Last**>" :

Cogsci7@gmail.com

THANKS SO MUCH FOR YOUR PARTICIPATION ☺

Experiment 1 Assessment Grading Rubric
*Points datums which count for cellular/molecular subscores are in parentheticals above [C] or [M]

FREE RESPONE ESSAY RUBRIC:
**Please see Appendix K, and rubric for molecular short answer questions below*

FREE RESPONSE SHORT ANSWER/WHAT-IF RUBRIC, CELLULAR QUESTIONS (What If's: 8-10)

1. Explain why neurotransmitter doesn't leak from synaptic vesicles into the synaptic bouton :

Extra + 1C/M pts. for each below :
Mention of hydro-carbon chains
Phosphate heads
Phospholipid Bilayer
Surrounded by Phosphate
2 pts.[C]
Phospholipids make it impermeable
1.5 pts. for ONLY below
Myelin Sheath ?
1 pt. max for below ONLY :
Neurotransmitters are enclosed in the synaptic vesicles ONLY so they don't leak out
The synaptic vesicles are impermeable to ions

2. Describe what ions are present near the synaptic bouton before it opens:

2 pts.
[Did not ask for this] Sodium Ions trigger the Calcium channels to open
1 pt. each
Na+ [C/M (m= molecular structure explicated)]
Ca+
.5
K+ [C/M]

3. Describe the process of neurotransmitters being released at the synaptic bouton from the first event that occurs with the synaptic vesicle ending with the point where neurotransmitter is released, in terms of cellular structures :

[describe the synaptic vesicle merging with the synaptic bouton in terms of cellular structures]
*2 (cell only)

- Then the synaptic vesicle opens up, exposing the neurotransmitter and the phospholipids that comprise the synaptic vesicle merge into the phospholipids of the synaptic bouton
  1
  Just saying the synaptic vesicle and bouton merge w/o mentioning phospholipids
  .5
- The cluster of Calcium ions at the end of the axon triggers the synaptic vesicle with neurotransmitter inside to move toward to end of the synaptic bouton
  .5
- The neurotransmitters that were inside the synaptic vesicles then move thru this opening in the synaptic bouton and out of the neuron entirely

4. Describe the structure present in the axon between one set of Sodium and Potassium channels and a second set of Sodium and Potassium channels, called a myelin sheath, and what function it serves :

1
"very thick" only, no phospholipid mention
+ 2C
Is a set of phospholipids
+ 1C extra
Many *layers/dense layer* of phospholipids
+1C extra
Is a set of phospholipids made of carbon-hydrogen bonds
CHECK FOR EITHER OF THESE, BUT NOT CREDIT FOR BOTH :
1
Insulates neuron

2 [C]
Insulates neuron so ions [particularly Na+] do not leak out of the neuron
1 [C]
No room for sodium and potassium channels
.5
Rapid/Speeds up conduction/transmission jumps for neural impulses
.25
Generates an action potential

5. Describe what triggers the action potential and explicitly describe the process by which this trigger was formed:

+1
Dendrites trigger calcium channels to open
One or the other
+1
Calcium triggers the action potential
+2 [+1 Key inference, C]
Calcium congregates at start of the axon hillock
.5
General notion of "ion" flow
.5
Just say excitatory input from dendrites, and nothing else

6. Describe where and how Sodium ions flow during the action potential :

1
Flow from outside to inside
1 [+1C <something in experimental video not in control>]
Flow in from top to bottom
1
From Sodium channels
1
Along their gradient

EITHER :
.5
At the axon
1
Initially from junction of soma and axon
OR
1
At node of ranvier/breaks in the myelin sheath
1 [+1C]
Flow to myelin sheath, which prevents leakage
1 [+1C]
And from there to adjacent Na+/K+ channels at the node of ranvier
1
"flow out along the axon"/toward the end of the neuron
<dissipate in the control text segment>
1 [+1C]
Flow from here to synaptic bouton/calcium channels/tail
1 [+1C]
Phosphate prevents leaking
.25
Sodium Channels close later

7. Describe what triggers that are located after a first set of sodium and potassium channels :

+2 [1c] <why not 2c ?>
Sodium
"Sodium molecules dissipate"

3 [2c]
Sodium from the previous set of channels
+4 [3c]
Sodium ions cluster together from first channel
1
Action Potential from the first set of channels
.5
Next set of channels are depolarized
.5
Ionic imbalances
+1 [1C]
Traveled thru the myelin sheath and was protected

8. Describe what affect increasing the number of calcium channels that are opened every time a neurotransmitter binds to dendrite receptors would have on signal transmission:

1
More calcium ions would enter
2[2c]
More calcium ions at junction of soma and axon
1[1c]
Increase positive charge in the neuron

1[1c]
More sodium channels triggered/triggered more often
1[1c]
More sodium enters the cell
1[1c]
More potassium enters the cell
1
More neurotransmitters released from the bouton (quicker/larger)
1
Signal would occur faster
1
Signal would last longer
1
More action potentials generated
1
Greater excitatory response

9. Describe what would happen if the amount of phospholipid was reduced in the area between the first set of Sodium and Potassium channels and second set of Sodium and Potassium channels :

***NOTE : control is never told myelin sheath is made of phospholipids, or explicitly that there are multiple sets of channels**

1
Slow down conduction speed/Decrease speed of the action potential
1[1c]
Sodium would leak out of the neuron
1[1c]
Potassium would leak out
1[.5c]
Ions would leak out of the neuron
1[.5c]
Decrease in ionic charge
1
Negatively affect the action potential
2[2c]
Decrease in number of Na+ ions reaching the second action potential
1[1c]

Action potential might not be triggered at second set of channels
1[1c]
Action potential would be slowed down at myelin sheath in between nodes of ranvier
1
Take more ions to trigger an action potential
1[1c]
Calcium channels would not open @ bouton
1
Neurotransmitter not released

10. Describe what would happen to signal transmission if the Sodium Channel was blocked :

1
No Sodium would enter the cell
1
Sodium would not flow to the end of the neuron
1
Signal would be blocked
2[2c]
Calcium ions would not trigger the first set of sodium channels to open
1[1c]
Second set of sodium channels won't get activated
1
No action potential/depolarization
.5
Ions won't come in
1
Neurotransmitter would not be released
4[4c]
Sodium ions would not trigger calcium channels to open and calcium ions would then not cause neurotransmitter to be released [@bouton]
2[2c]
Calcium ions would not trigger neurotransmitters to be released at the bouton
1
Process would not repeat in other neurons
1
Sodium/Potassium ion imbalance, more sodium outside than in

[MOLECULAR QUESTIONS (What-If's, 15-17)]

11. Describe what the structure present in the axon between one set of Sodium and Potassium channels and a second set of Sodium and Potassium channels, called a myelin sheath, looks like at the molecular level (again, using molecular terminology) :

1
Layer of phospholipid
1.5
Three layers of phospholipids
4[4m]
Phospholipid is made of phosphate heads and a hydrocarbon tails
3[3m]
Layers of carbon-hydrogen chain molecules
1[1m]
Layers at the top and bottom
4[4m]
Two hydrocarbon tails, made of hydrogen and carbon
2[3m]
PCH2-PCH2
1[2m : if in terms of hydro-carbons]
Arranged in mirror image/symmetric

12. Compare the R-subunits for Sodium vs. Calcium channels and how the differences/similarities between the R-groups effects how each channel functions :

[1m]

Both have 2 R-subunits

2[3m]

R-subunits press together and separate when positive ions trigger them

2

Requires different ions to bind to channel/open channel

1[1m]

Mentions differences in colors of subunits

2[2m]

Red/Green subunits allow Sodium in

4[4m]

Red/Green, Pink/Brown

1[1m]

Sodium R-group attracts Sodium

1[1m]

Calcium R-group attracts Calcium

1[1m]

Different ions flow through b.c. R-groups are different

1[1m]

R-subunits made up different atoms and molecules

3[3m]

Different ions bind to R-subunits b.c. different structures, changing their shape

2[2m]

R-subunits move farther/closer together to let ions in

3[3m]

R-subunits are connected by binding the carbon with a nitrogen-hydrogen molecule

3[3m]

Carbon is bonded to a nitrogen group and an oxygen

13. Describe how the Sodium channel works at the molecular level :

2

Opening channel gate allows ions to come in

2[2m]

Green/Red Subunits

1

Sodium enters the neuron

4[4m]

Sodium binds to two R-subunits, causing them to separate and open

3[3m]

Channel opens when two R-groups move apart

2[2m]

When R-subunits move back together, channel closes

2

Calcium trigger Sodium channel to open

3[3m]

Calcium triggers R-subunits to open

2

Open when positive ions

2[2m]

Bound by nitrogen and oxygen molecules

10[10m]

Is a protein, with a NH2-C-R-subunit-C-O-NH-C-R-subunit-C-O-OH

4[4m]

C-N-H bond outside the R-group

5[5m]

R-groups joined by C-N-H bond, which then repeats
3[3m]
Carbon chains w/oxygen in the middle + Nitrogen at the borders
1[1m]
More Na+ in the neuron, Sodium Ion is positively charged

14. Describe the various points along the process where positive charge enters or exits the neuron.

1
Positive charge comes in
1
Positive charge builds up
1[1m]
Calcium entering has positive charge
2[2m]
Calcium entering has positive charge, and decrease in positive charge outside
1[1m]
Sodium positive
1
Ions exchange
2[2m]
Positive charge in axon as action potential progresses
2[2m]
Charge outside of neuron becomes more negative
2[2m]
Changes from positive to negative with Sodium influx and Potassium efflux
1[1m]
Same thing repeats with second set of channels
2[2m]
Calcium positive ions inflow at the synaptic bouton
1[1m]
Overall positive charge in the neuron before neurotransmitters are released
3[3m]
Potassium exit makes charge neutral again
1[1m]
Ions are all positive
2[2m]
Differences in the build up of charge

15. What if the R-groups for Sodium channels were switched with the R-groups for Calcium channels, what would happen :

2
Sodium could not enter the Sodium channel
2
Sodium could leak out
4
Channels would switch what ions they let into the neuron
4
Action potential would not occur if sodium reached the axon hillock instead of Calcium
2[.5m]
Electric charge would be hindered
3
Signal would not occur, b.c. calcium ions would not enter the axon
3[1m]
Switching group changes makeup of the protein
1
Channel would not work
1
Action potential would not occur

16. What would happen if one of the R-groups for the Potassium channel was deleted :

1

Cell can't return to resting state

1

Cell will continue to fire

1

Potassium channels will not open

2[2m]

Phosphate might enter gate

1

Hole in Potassium gate

1[1m]

Would not be a functional protein

1

Neuron would become increasingly positive

2

Potassium would freely enter uncontrolled

1

Impair action potential

2

Any passing Ions would leak out of the channel

1[1m]

Protein would be incomplete

1

Channel would not work

17. If a neuron was created where the phospholipid has three hydrocarbon tails lined up in a row how would this effect signal transmission in the axon, specifically:

1

More signals would be released

3[3m]

Phospholipid layer may not allow R-groups of protein channels to embed themselves into the membrane

2

Leakage would be less likely in the membrane

1

Stronger transmission

2

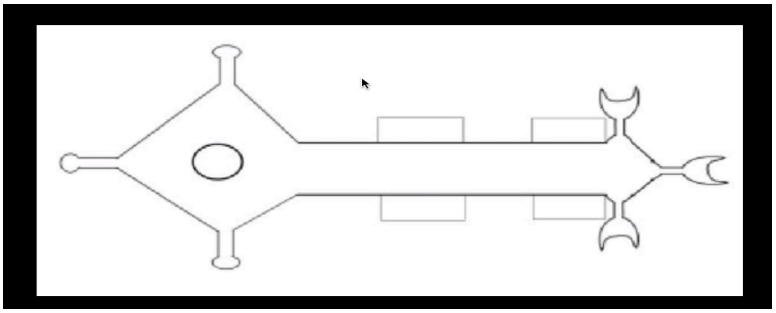
No sodium ions would enter and no signal would generate

<under assumption that phospholipids would block the channel>

Appendix E : Control Conditions Slides and Presentation Notes

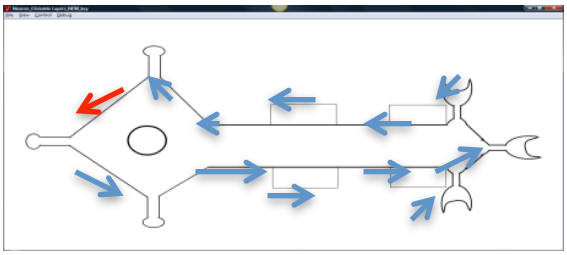
Control : Isolated Images

I. First, key structures on the neuron were pointed out on the wireframe along with small images representing these structures (dendrites, phospholipids, calcium channels etc.) as an introduction to the lesson. This introduction was matched in content to the introduction for the experimental condition.



STEP 1 : Control : Cellular Level : Neurotransmitter binding to dendrite and phospholipid structure

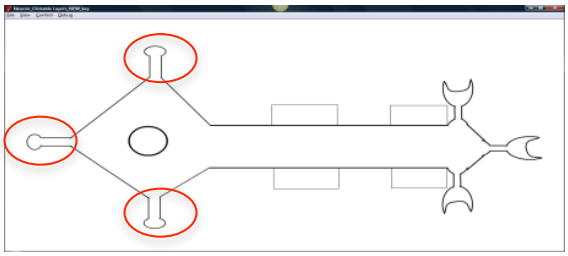
Dendrite pointed out on wireframe model below : cursor follows along membrane edge where arrows are



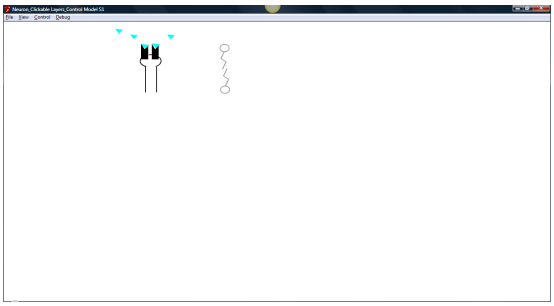
Explanation of phospholipid as a unit of the membrane

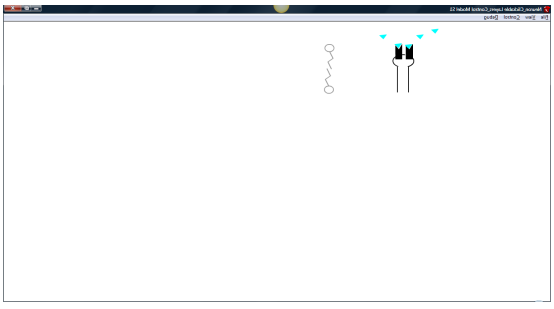
*Explanation repeated so exposure to concept is in line with experimental

Three locations where dendrites are found are pointed out on the wireframe model below :



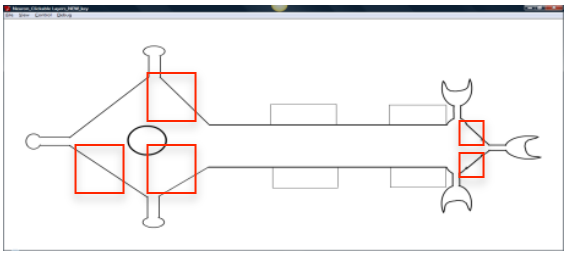
Dendrite Explanation and Animation of Neurotransmitter binding to Dendrite, see screenshots below (again concept explanation repeated so number of instances of exposure to concept is the same in the control and experimental) :



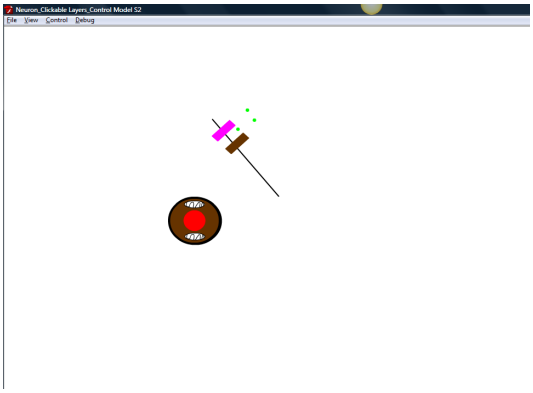


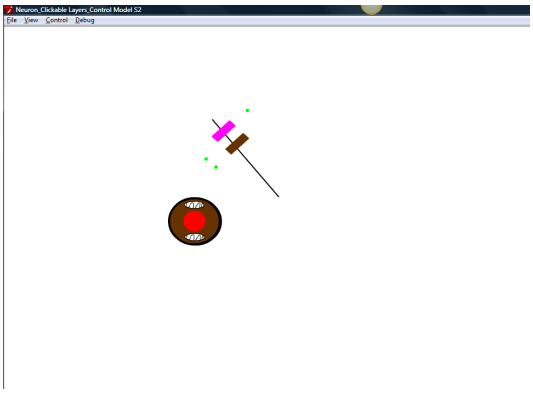
STEP 2 : Control : Cellular Level : Calcium channel opening/closing and Ca ion flow

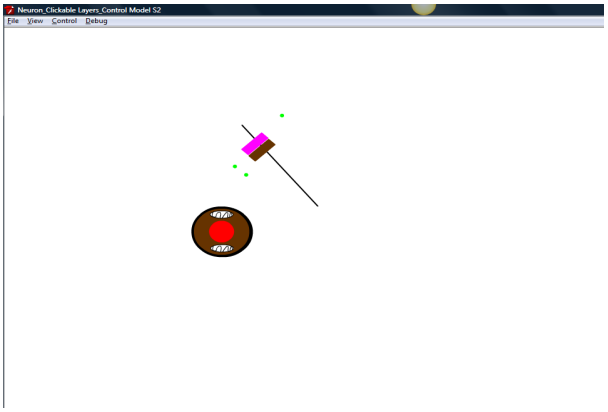
The five locations where Calcium Channels are found are pointed out on the wireframe model below



Calcium Channel opening and Calcium ion flow thru Channel Explanation and Animation see screenshots below (again concept explanation repeated so number of instances of exposure to concept is the same in the control and experimental) :

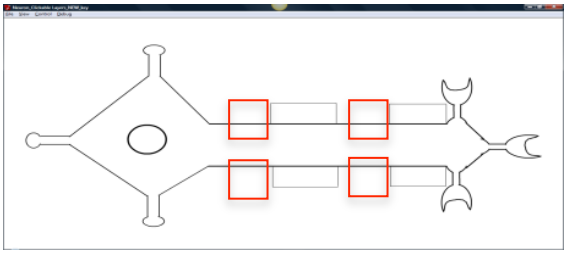




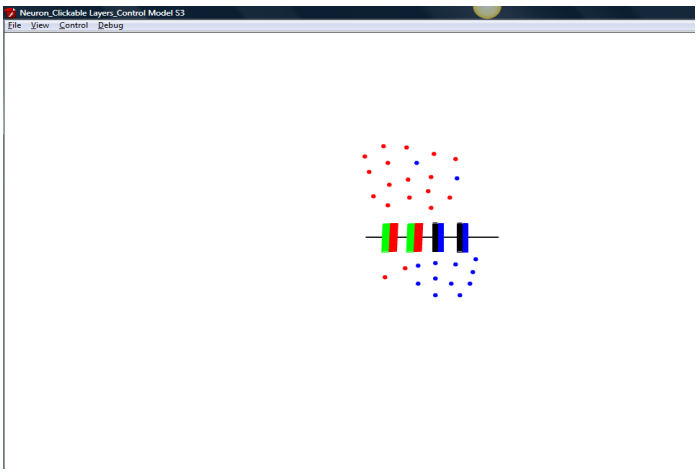


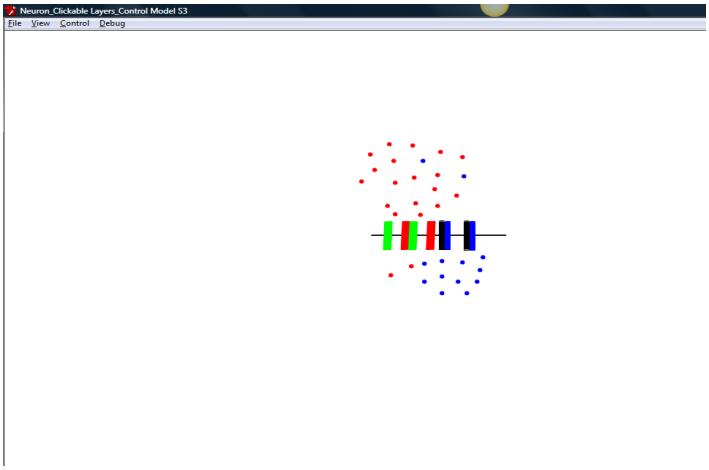
STEP 3 : Control : Cellular Level : Action Potential Propagation

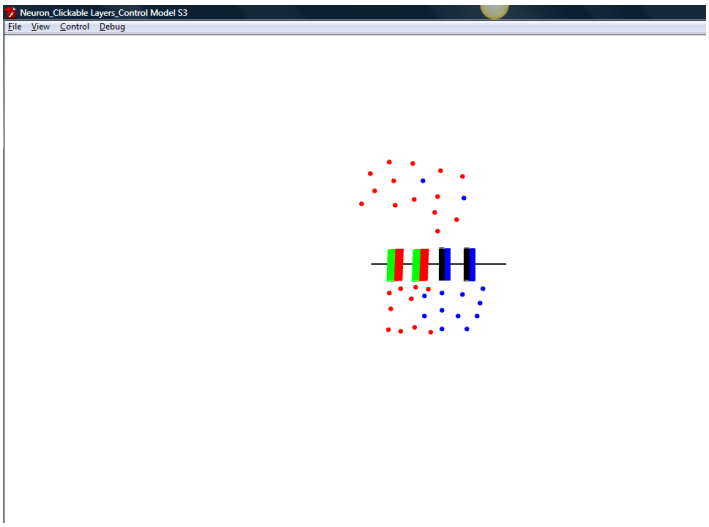
The four locations where Sodium and Potassium Channel Action Potential Channels are found are pointed out on the wireframe model below :

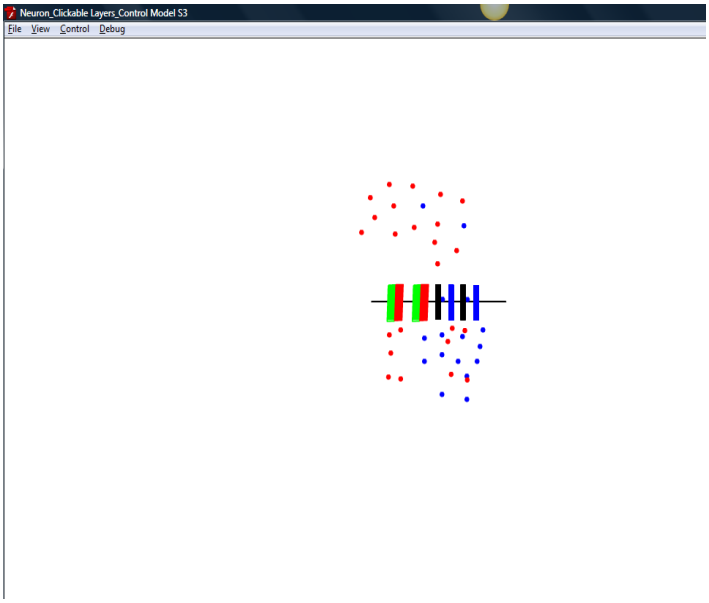


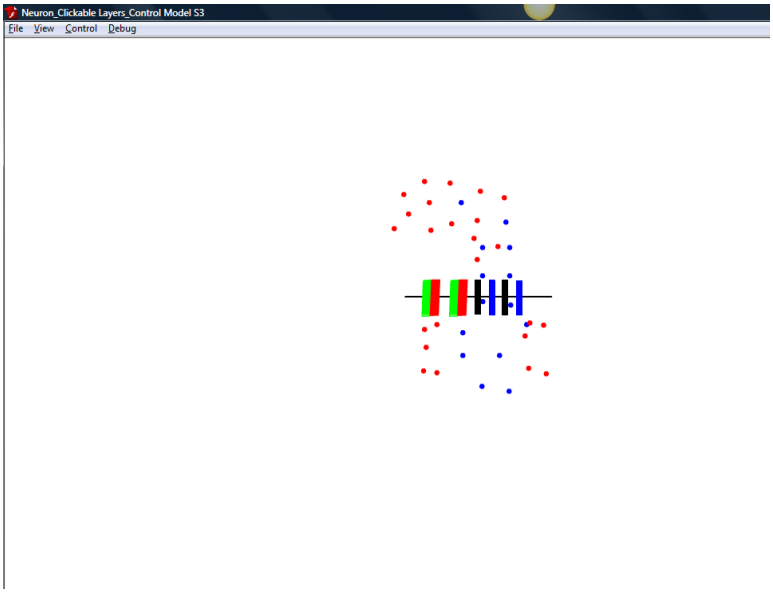
Then an animation of Sodium influx and Potassium Efflux are shown, see screenshots below (again concept explanation repeated so number of instances of exposure to concept is the same in the control and experimental) :

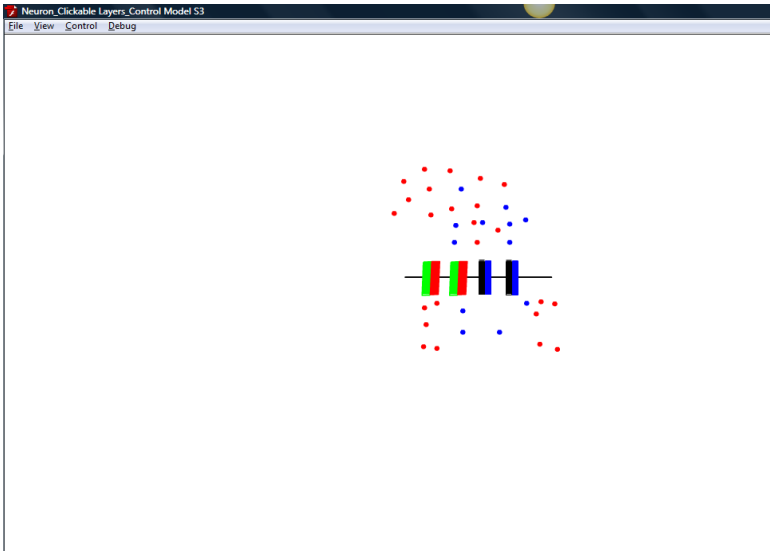



Neuron_Clickable Layers_Control Model S3
File View Control Debug


Neuron_Clickable Layers_Control Model S3
File View Control Debug


Neuron_Clickable Layers_Control Model S3
File View Control Debug

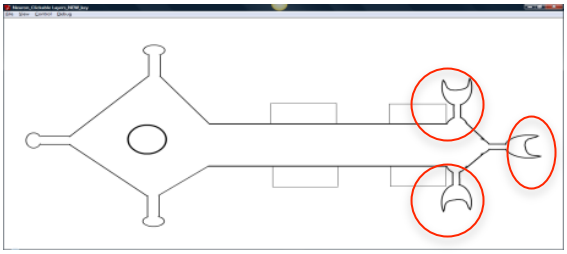




STEP 4 : Control : Cellular Level : Calcium Channels at Synaptic Bouton Opening and Calcium Ion Influx (Shown shown explicitly, because calcium channel and locations already shown in STEP 2)

STEP 5 : Control : Cellular Level : Synaptic Bouton release of Neurotransmitter

The three locations where the synaptic boutons are found are pointed out on the wireframe model below :



Then an animation of the vesicle binding to the synapse and neurotransmitter release is shown:

Appendix F: Verbal Transcript for Control Condition

Structural : Wireframe

Hi, today we're going to learn about the neuron

Let's go over the basic structures that comprise a neuron by examining this structural model of the neuron

The dendrites are located at these locations,

The calcium channels and ions located at these locations,

The sodium and potassium channels and ions are located, here, here, here and here,

This entire area is called the axon

And the phospholipids run all along the membrane of the neuron, especially in these rectangles here

The synaptic bouton and synaptic vesicles are located, here, here and here

*Great, now that you have a basic overview of the neuron we will view the cellular model of the neuron and look at these structures in greater detail

BASIC CELLULAR OUTLINE OF THE NEURON

The first structure we're going to learn about are phospholipids.

They run all along the neuron, esp. within these spaces here <myelin sheath 4 rectangles>, all within this space here, and this space here

And they look like this : <show phospholipid>

Each phospholipid is comprised of a phosphate head and a tail of carbon and hydrogen that extends from this head.

Okay great, now let's go to the second structure :

The dendrites are located here, here and here, let's see what they look like at the cellular level

These neon blue structures are neurotransmitters

These black structures are dendrite receptors.

<play animation>

The first step in the signal transmission in the neuron, is that neurotransmitters released from a neuron nearby move towards the dendrite receptor and bind to the dendrite receptor.

STEP 2

Another important structure are calcium channels and ions, <point out on wireframe, 5 x)

These green ions are Calcium ions and are positively charged.

This is a calcium channel, as you can see it has two subunits, a pink and brown one.

<play animation>

- Once the neurotransmitter binds to the dendrite receptor the Calcium channels in the Neuron open up and positive Calcium ions flow into the neuron

- Then these Calcium channels close

STEP 3

<Sodium and Potassium channels are located in cluster in the neuron> point out where

This area is called the axon, let's see what these structures look like at the cellular level.

Here, we see sodium and potassium channels

These are Sodium channels, comprised of green and red subunits

These are Potassium channels, comprised of black and blue subunits

These red dots are Sodium ions, and are positively charged

The blue dots are Potassium ions, and are also positively charged

The third step of signal transmission is that Dendritic signals mediated by Calcium are integrated right before the first set of charge gated sodium channels, opening them, which begins a series of events called the action potential

- First, this causes positively charged Sodium to enter the axon, as sodium channels open
- After a while the Sodium channels close
- Then Potassium channels open and positively charged Potassium ions leave the axon, this balances out the new sodium ions that just entered the axon, so the number of positive ions inside the axon remains the same.
- As this is occurring, the positive Sodium ions that previously entered the axon, dissipate along the axon, generating action potentials, further along the axon as the Potassium channels close.

This is the last step in the action potential

<point out synaptic bouton and vesicles on wireframe>, let's see what these structures look like at the cellular level

STEP 4/5

STRUCTURES :

<point to synaptic bouton>

This again, is the synaptic bouton

<point to synaptic vesicles>

Within each bouton are a few of these synaptic vesicles, which are membranes of spheres which blue contain neurotransmitter molecules

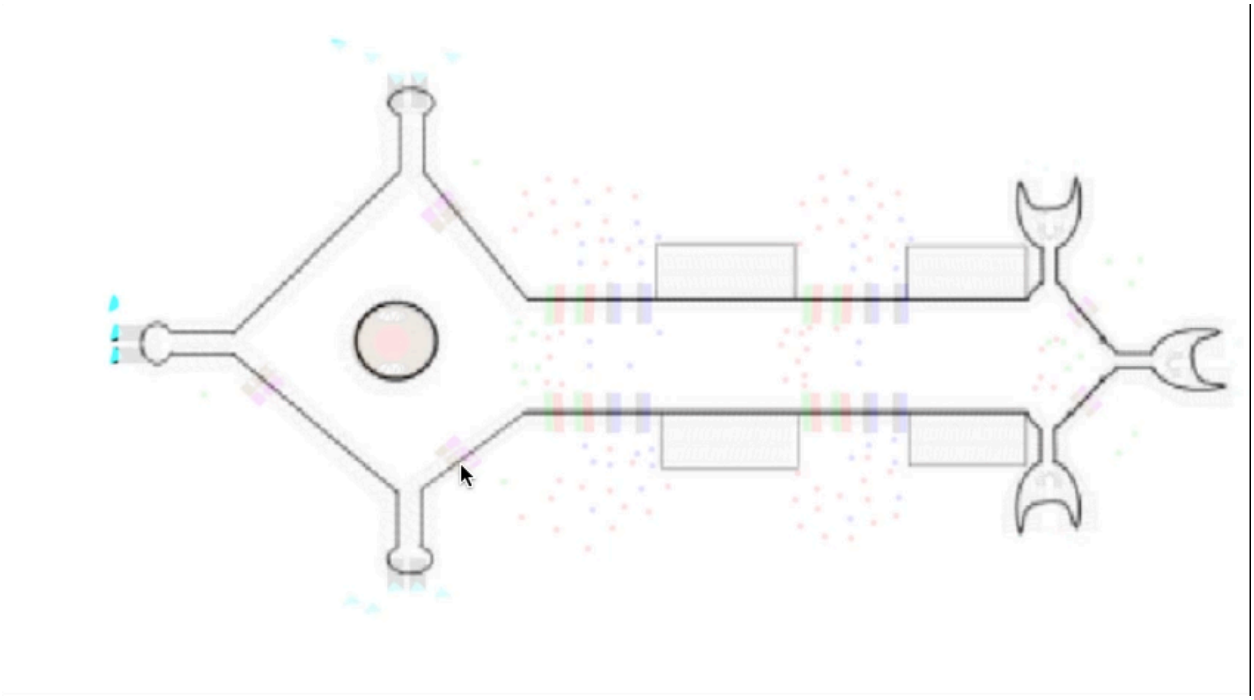
<play animation>

- As a result of Calcium channels triggered by the action potential opening, the synaptic vesicle mergers with the synaptic bouton, and creates an opening for neurotransmitter to exit the neuron

If a second neuron was nearby these neurotransmitters would bind to the dendrite receptors of this neuron and the entire process we just went thru

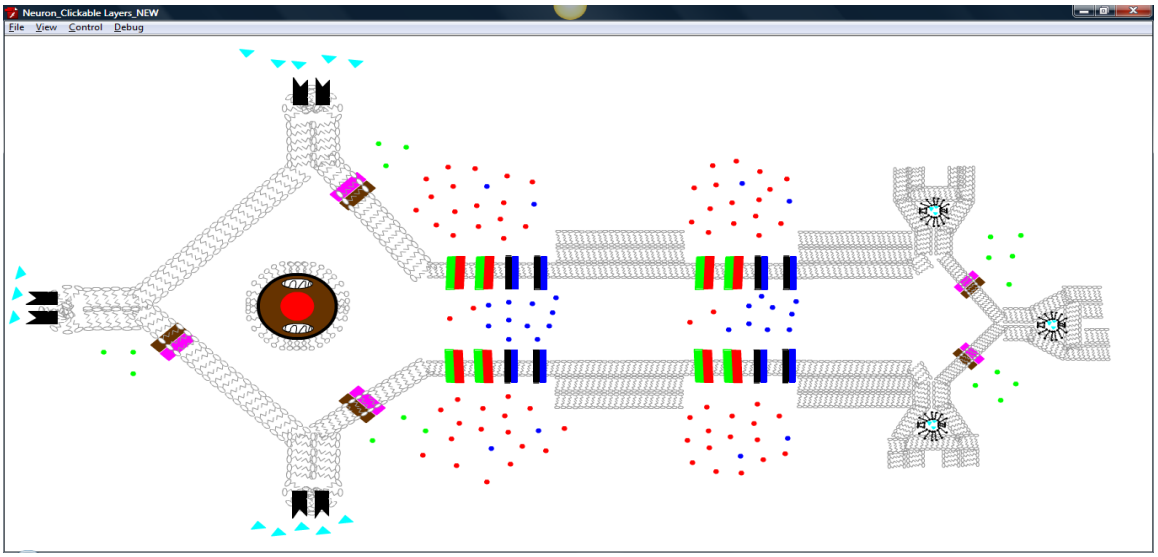
APPENDIX G: Experimental Condition Slides and Notes

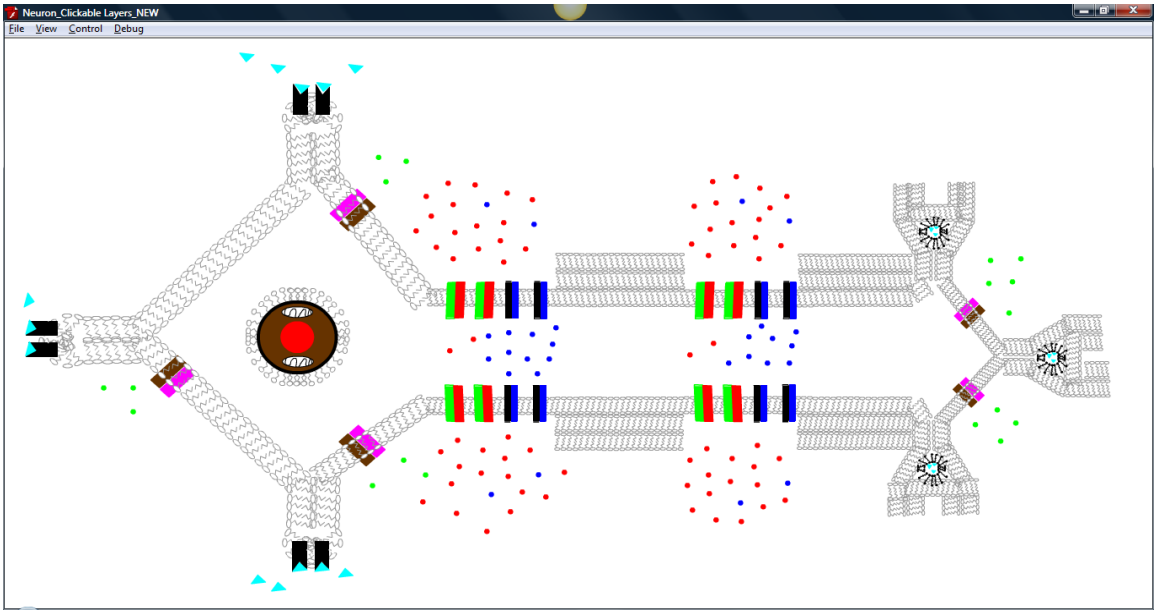
Introduction : Point out major structures on wireframe, with cellular structures lightly in the background



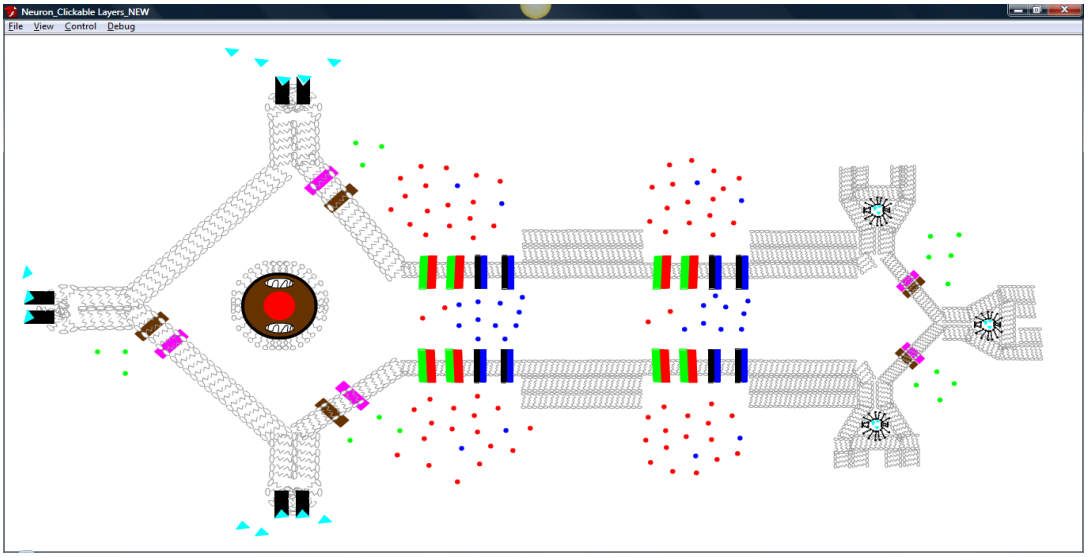
STEP 1 : Experimental : Cellular : Neurotransmitter (Ach) binding to Dendrite receptor

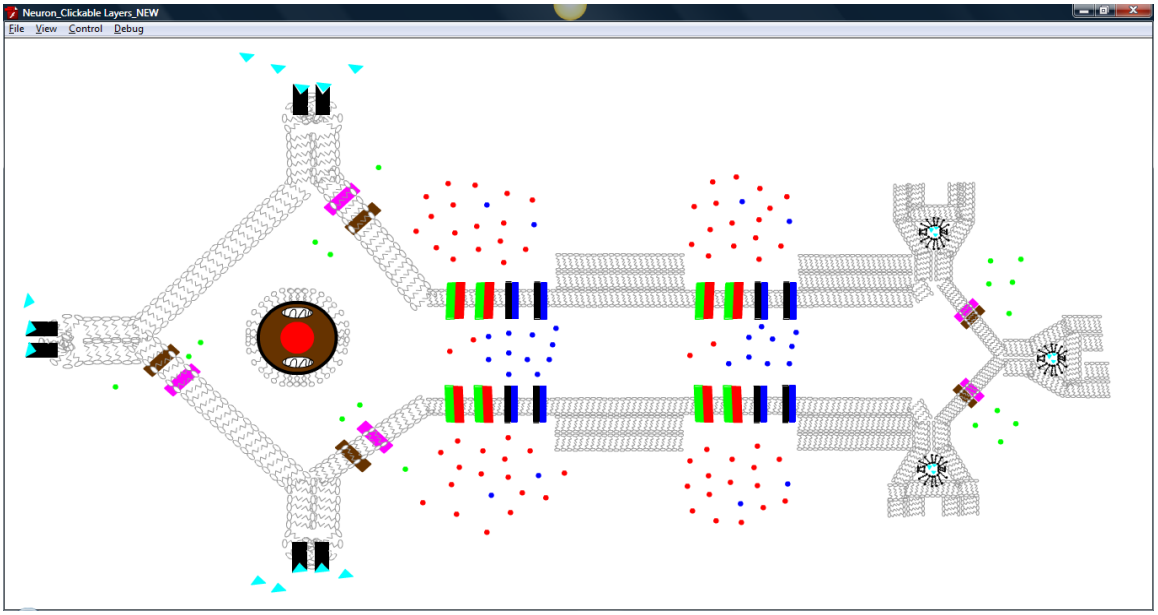
Phospholipid structure zoomed in on, and explained in context of entire animation

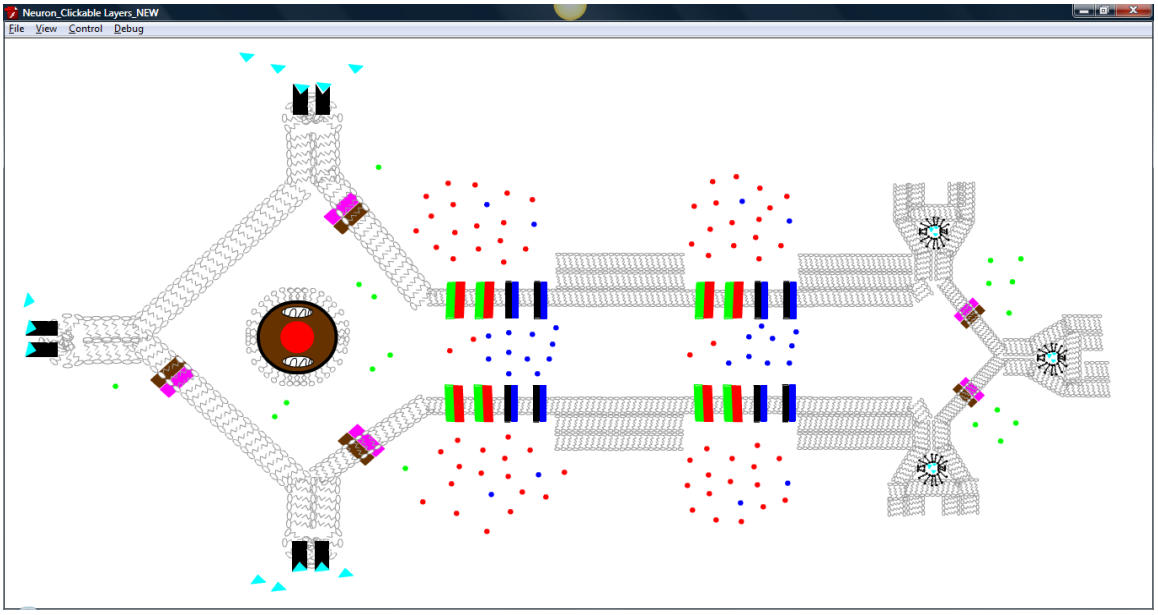


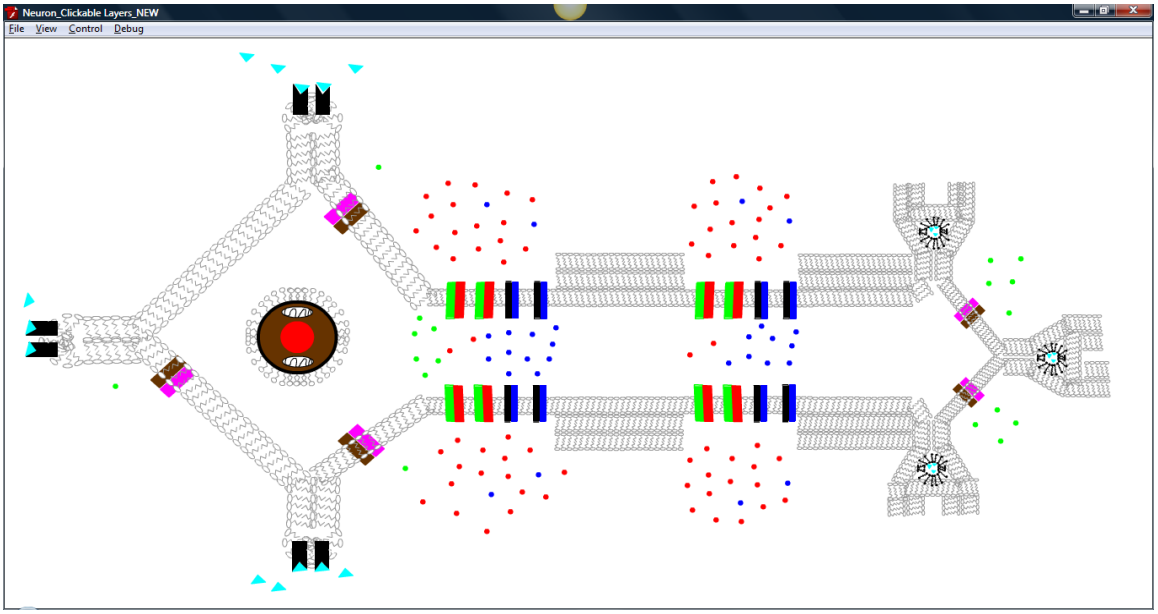

Neuron_Clickable Layers_NEW
File View Control Debug

STEP 2 : Experimental : Cellular: Calcium Channel @ Soma opening

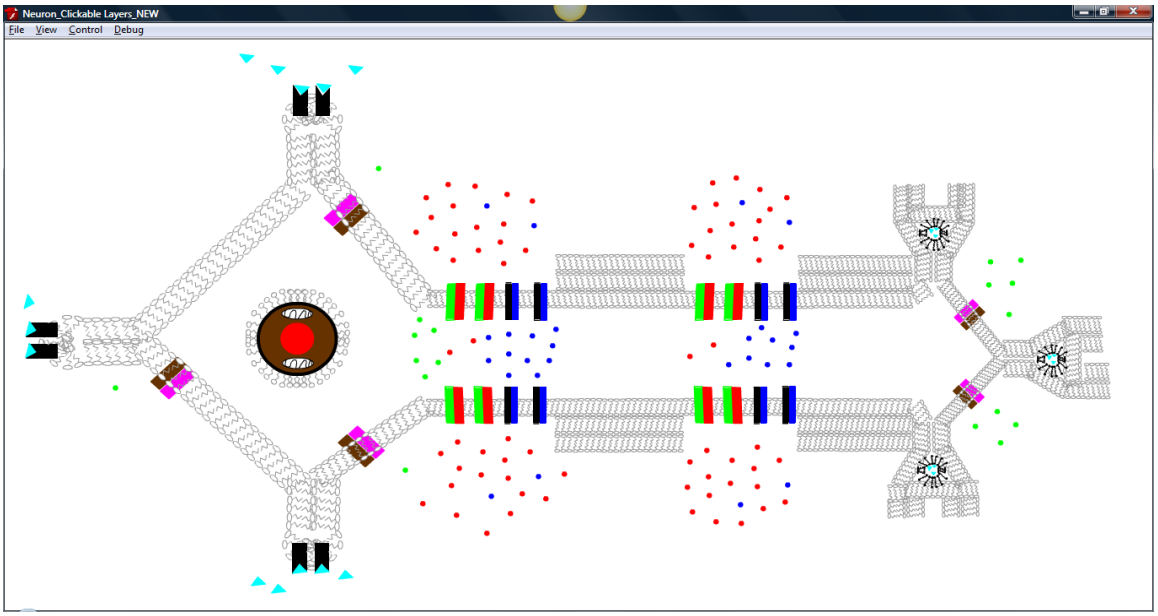


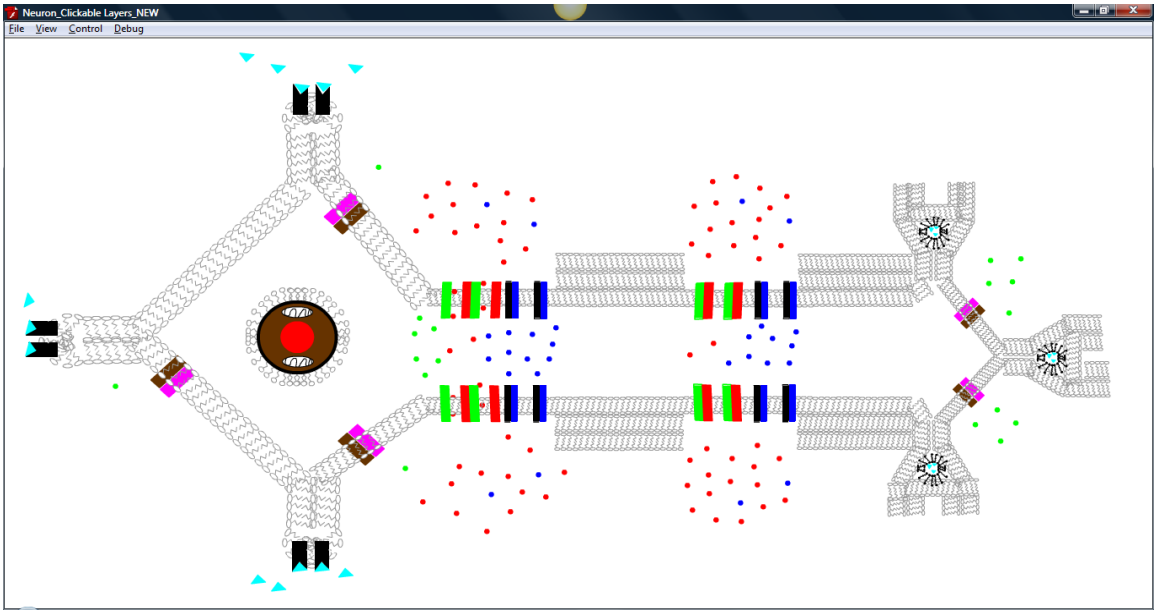


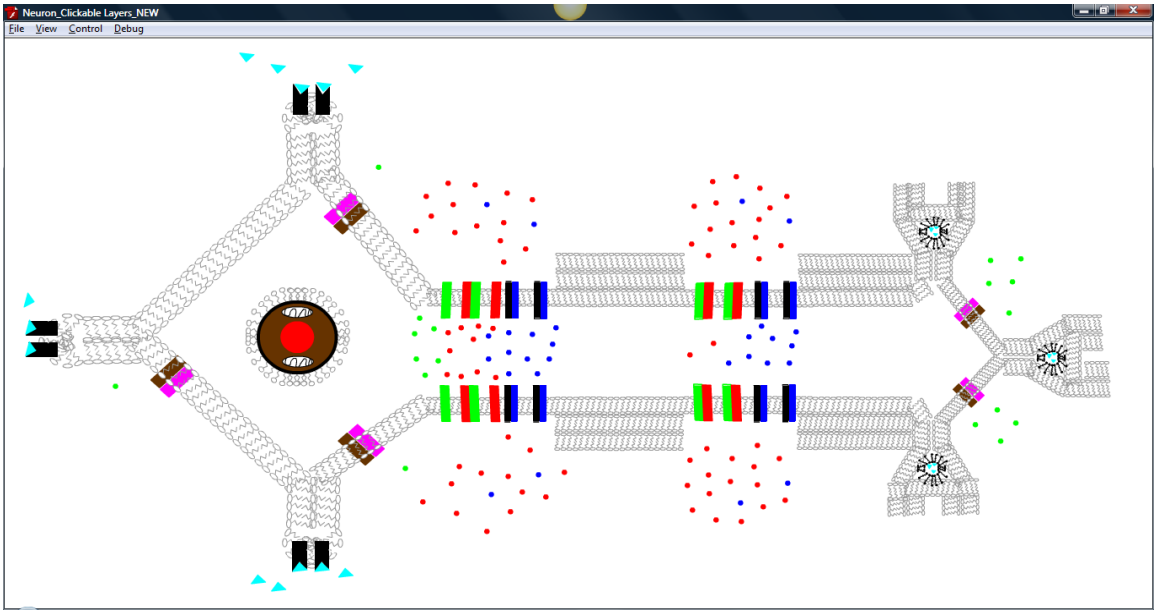

Neuron_Clickable Layers_NEW
File View Control Debug


Neuron_Clickable Layers_NEW
File View Control Debug

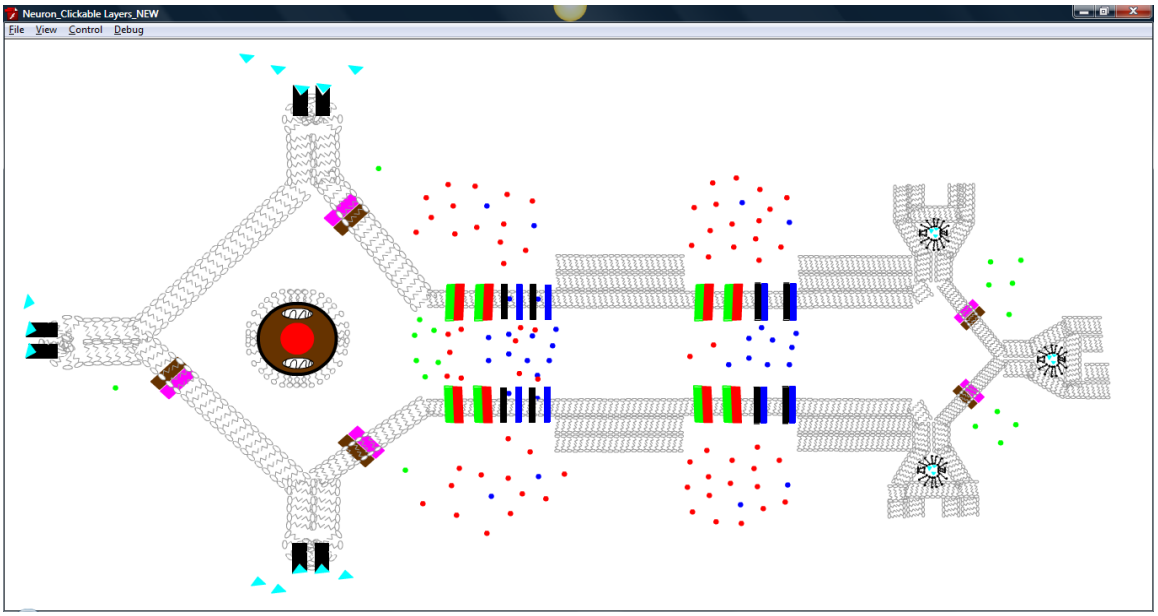
STEP 3 : Experimental : Cellular: Action Potential Propagation

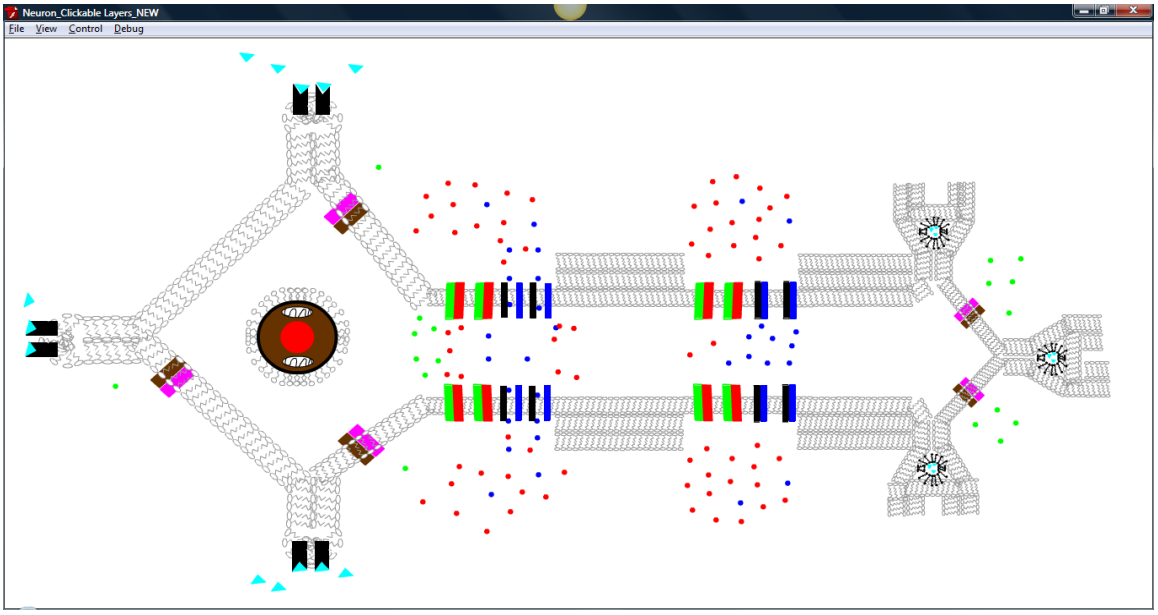


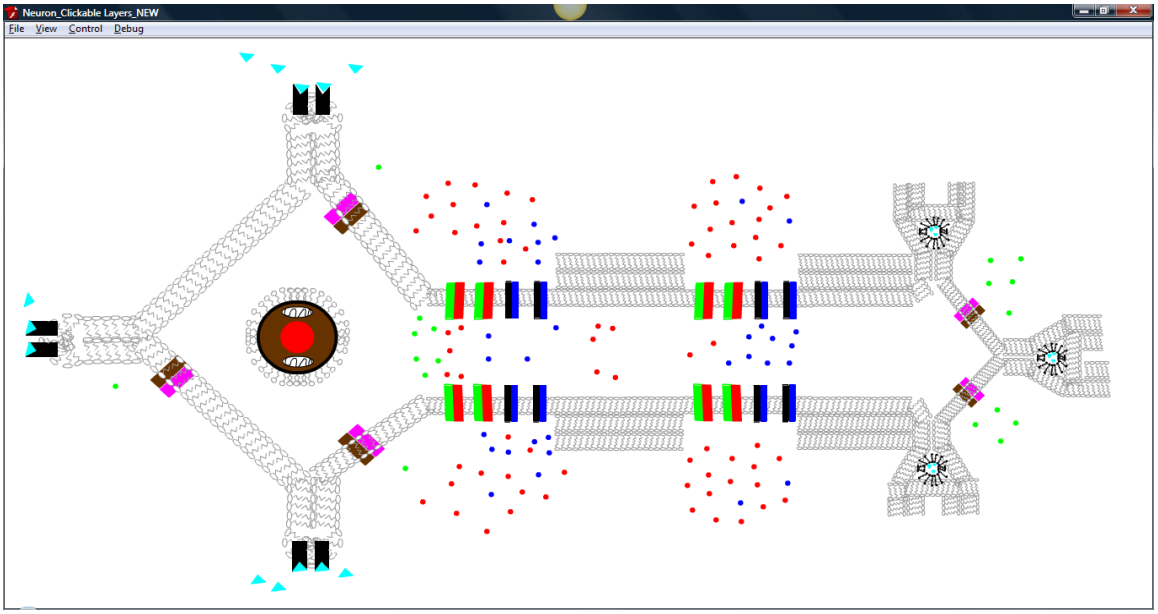




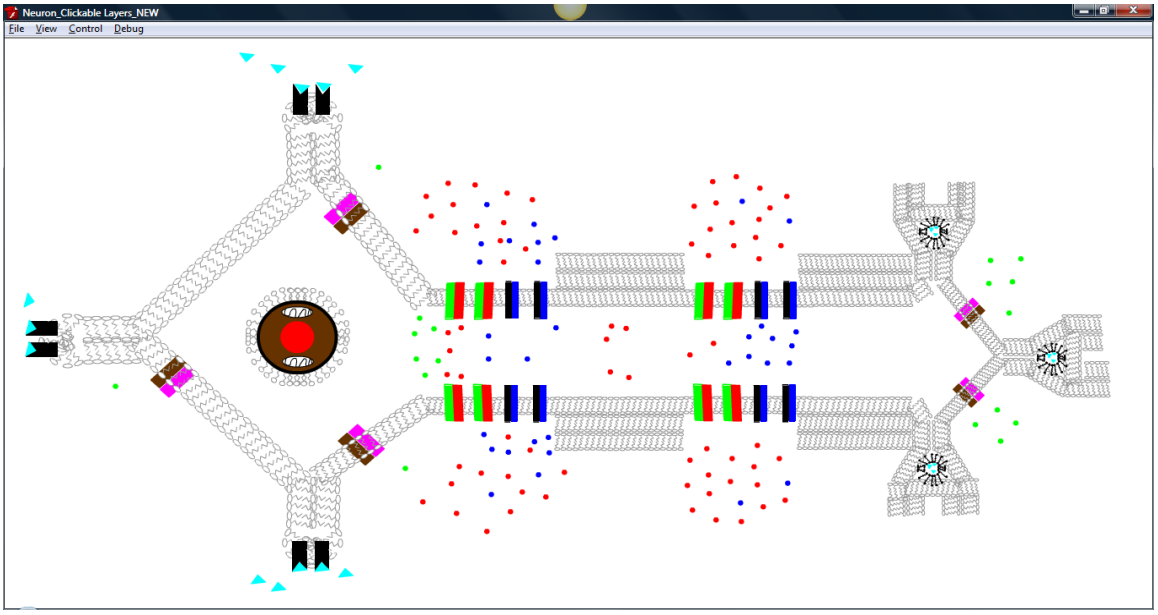
Potassium Channels Opening :

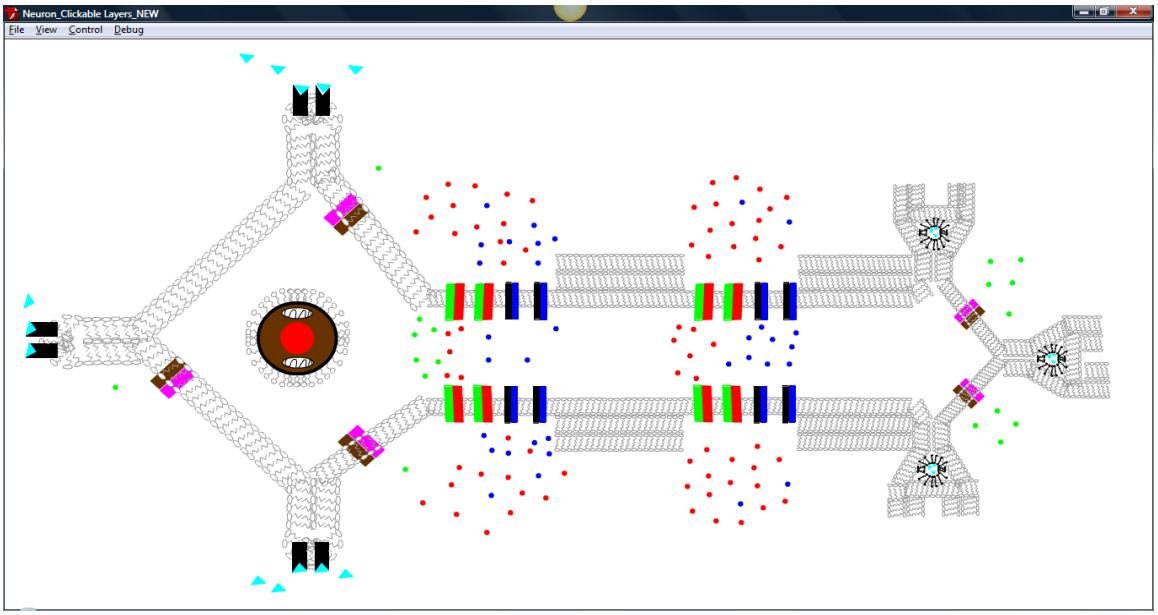






Sodium dissipating through myelin sheath :


Neuron_Clickable Layers_NEW
File View Control Debug


Neuron_Clickable Layers_NEW
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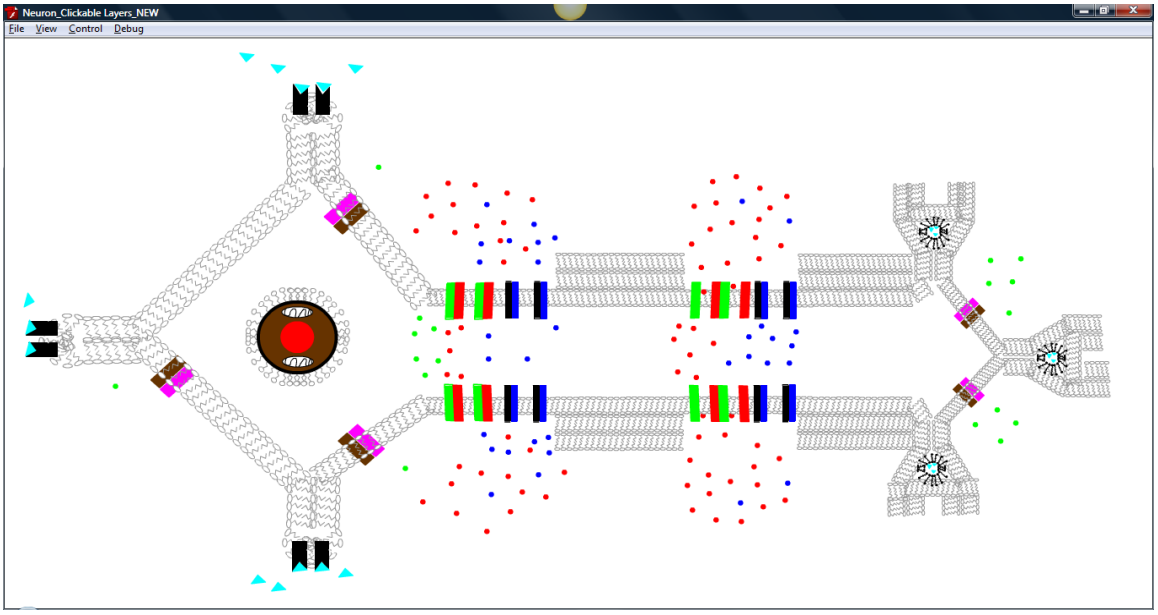
Neuron_Clickable Layers_NEW
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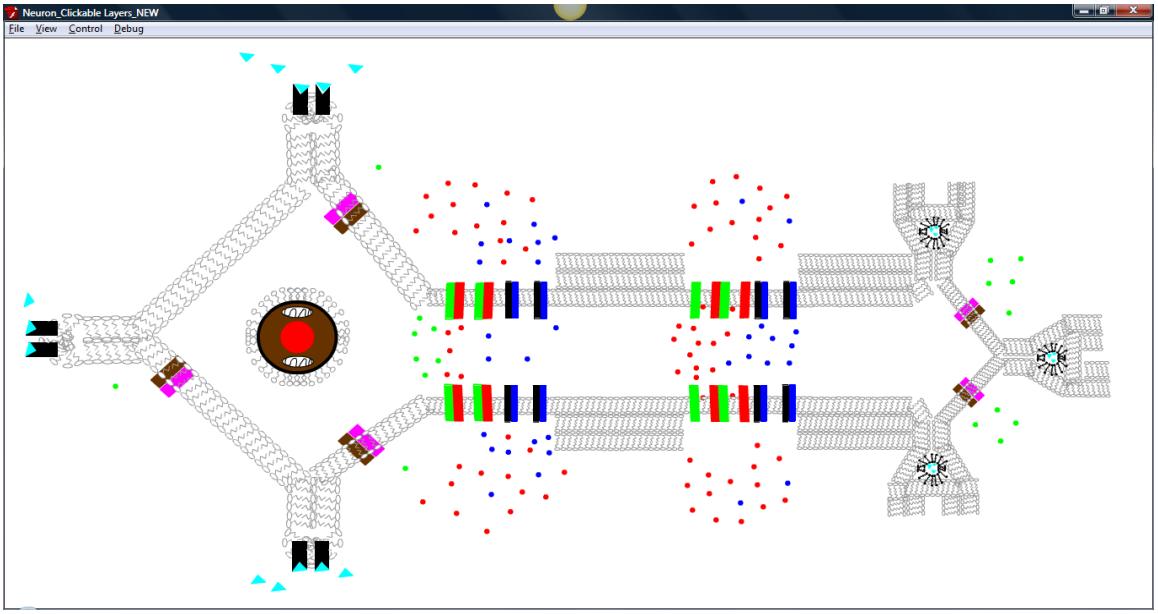
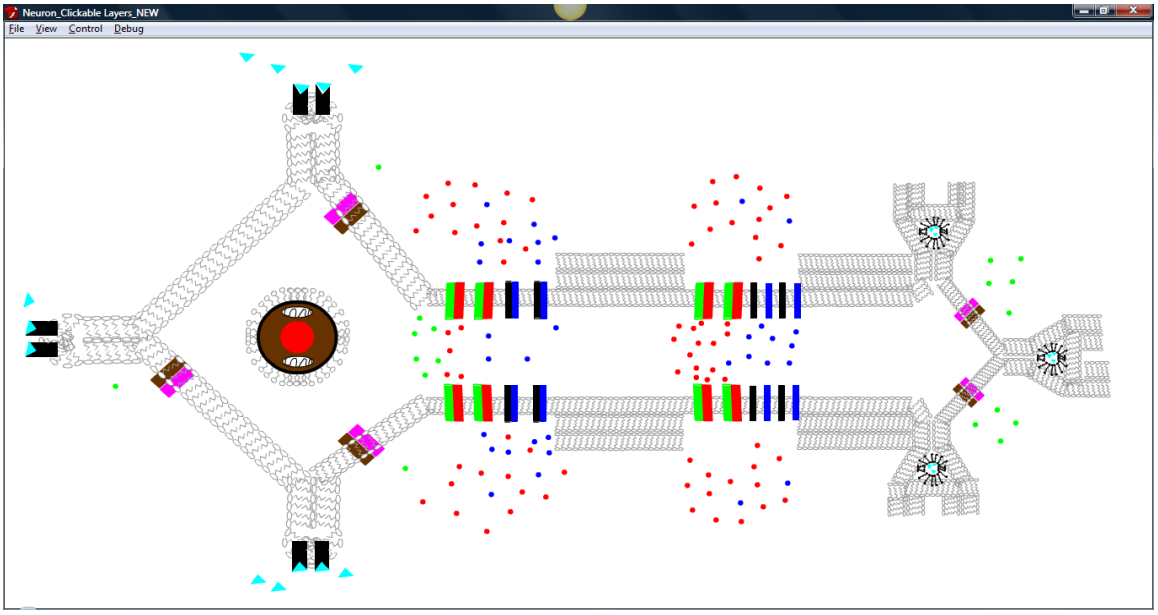

Neuron_Clickable Layers_NEW
File View Control Debug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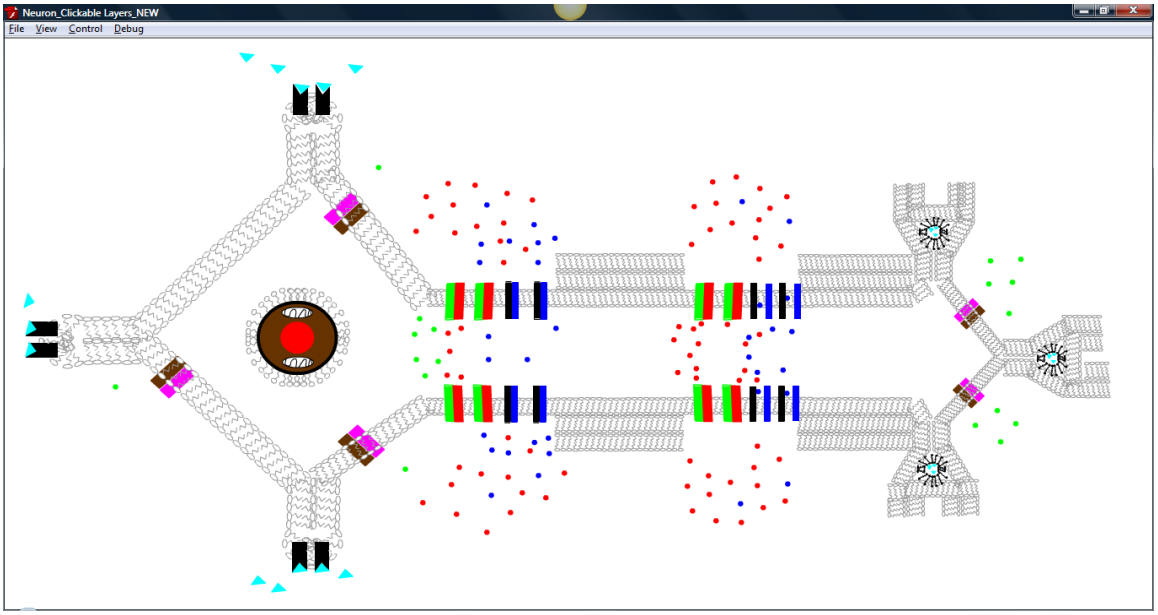
Neuron_Clickable Layers_NEW
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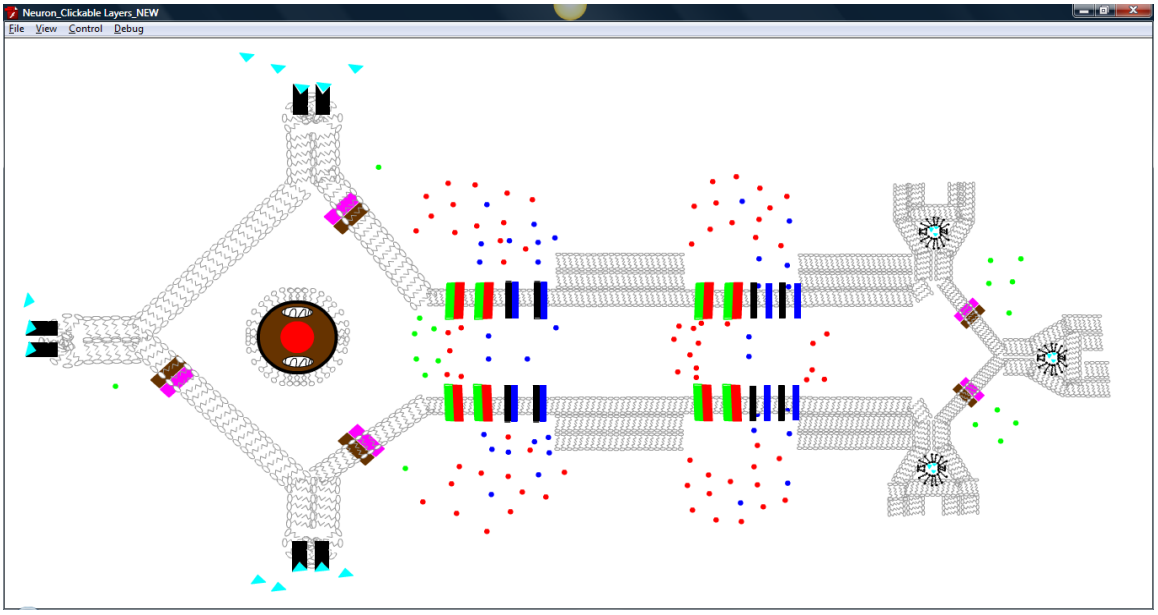
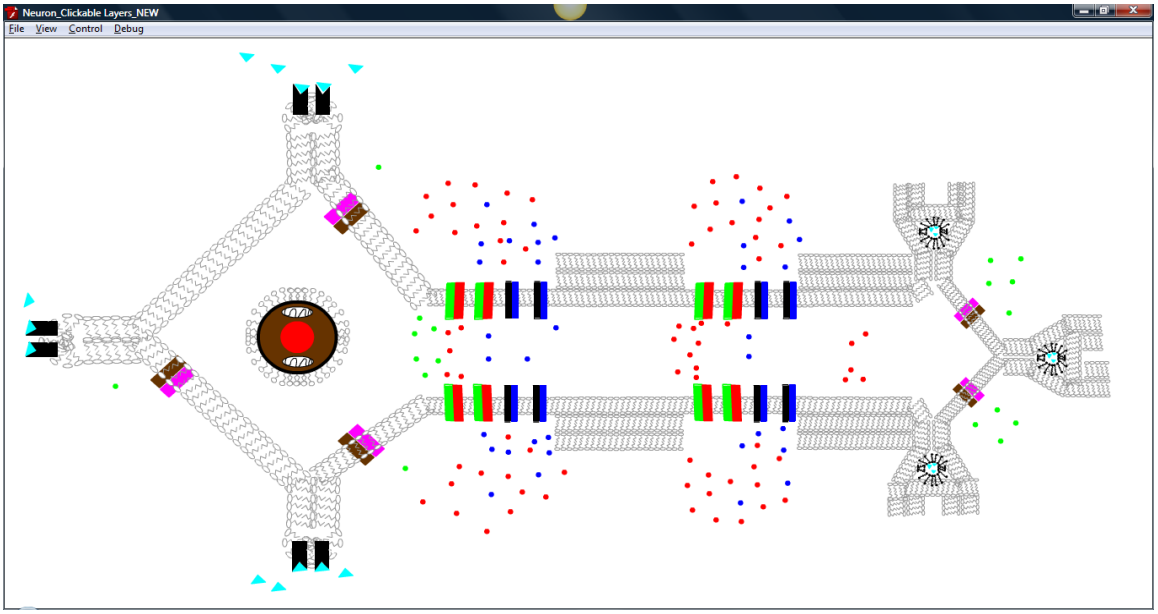
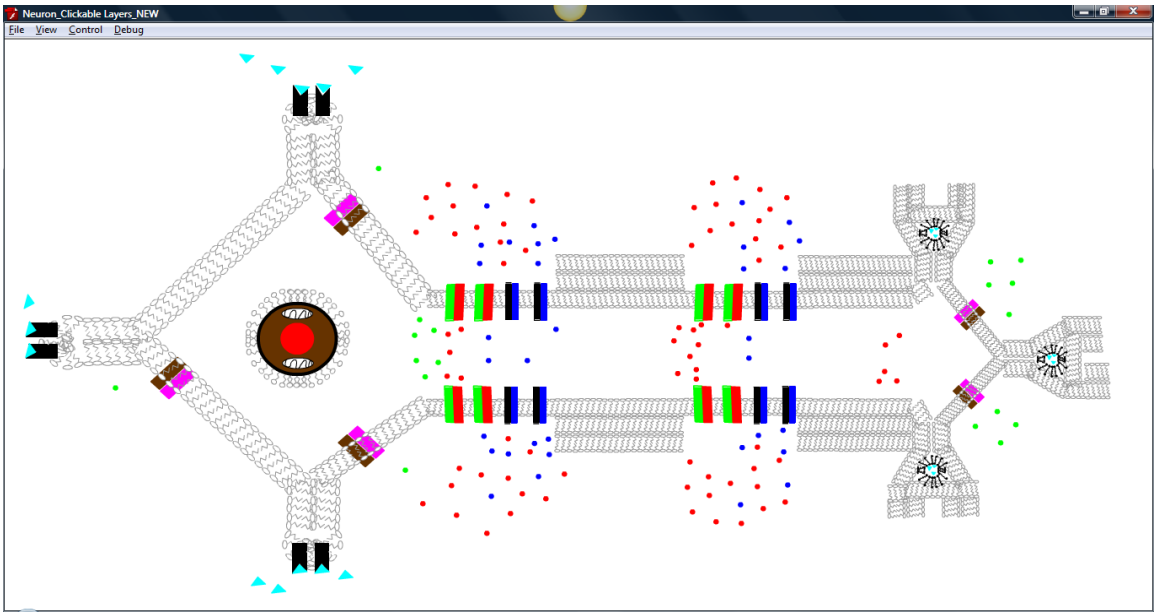
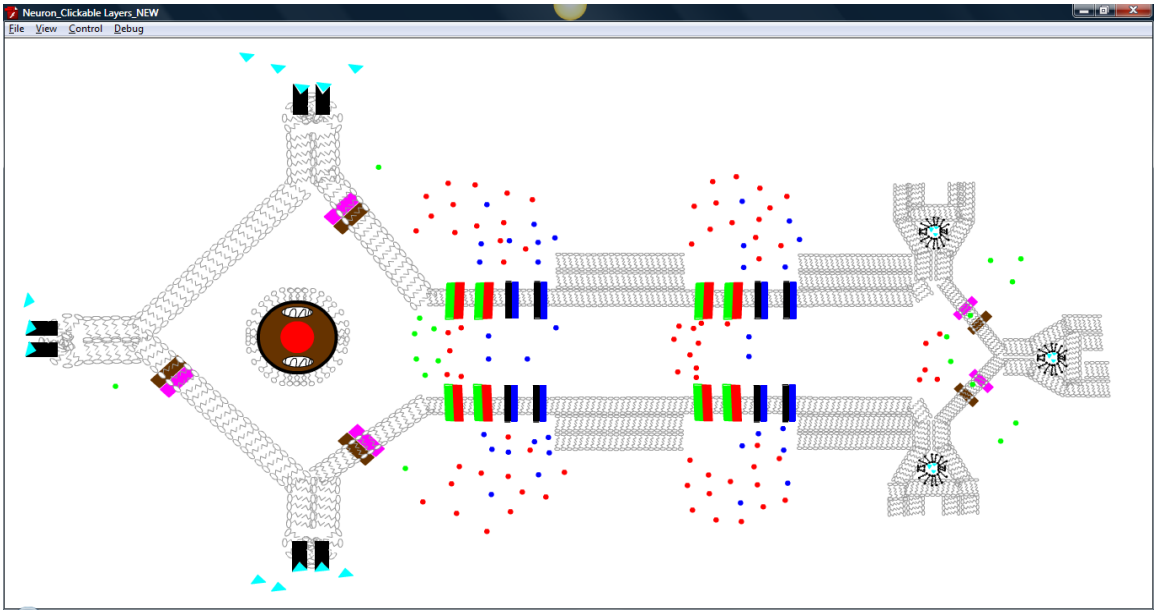
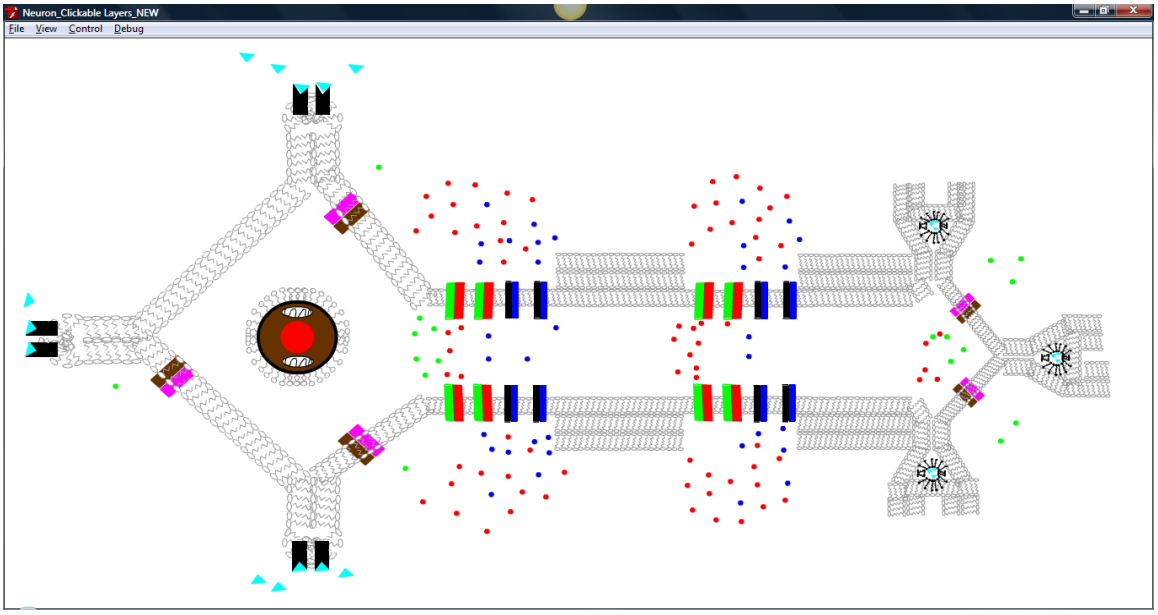

Neuron_Clickable Layers_NEW
File View Control Debug


Neuron_Clickable Layers_NEW
File View Control Debug

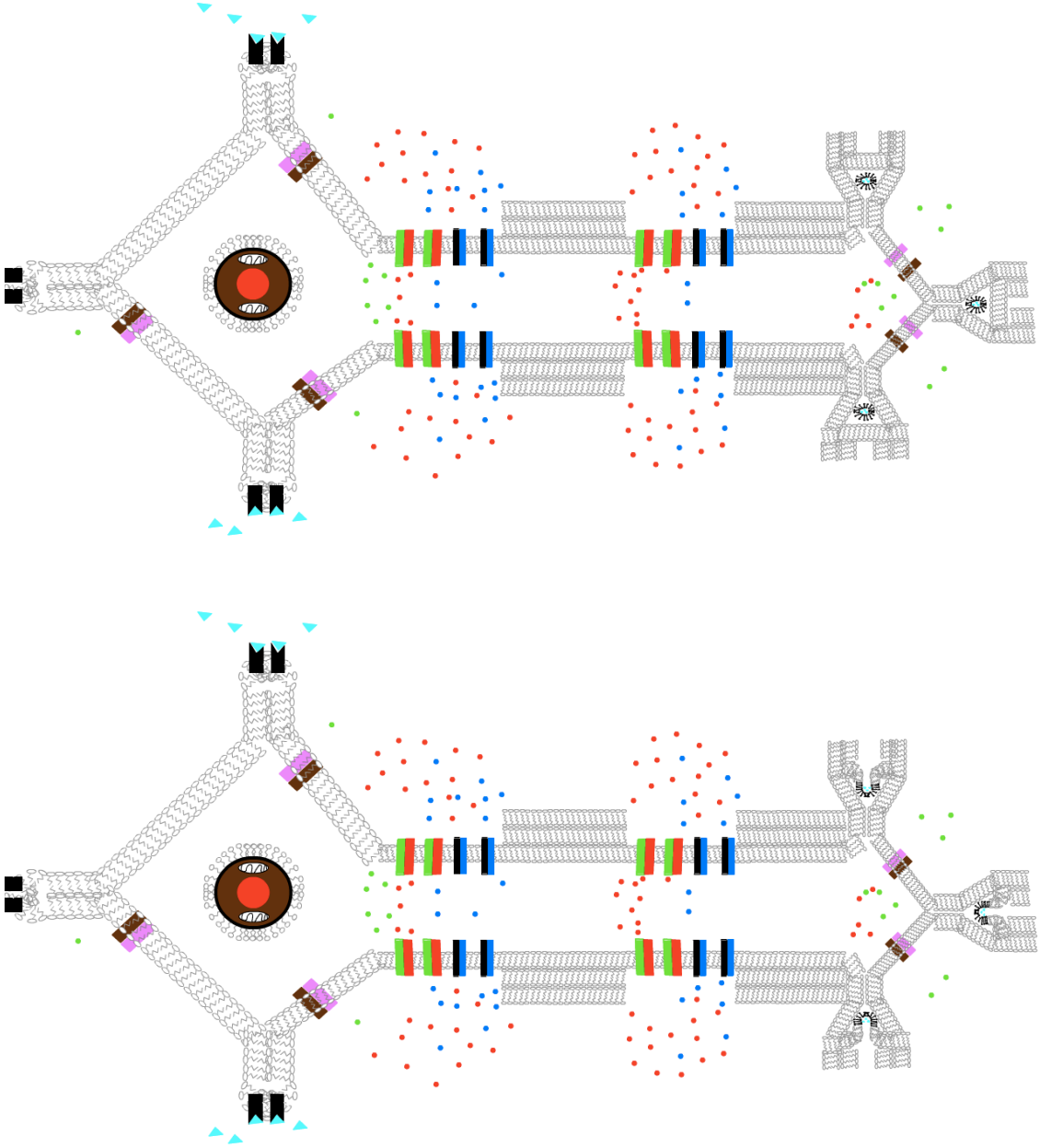
STEP 4 : Experimental : Cellular : Calcium Channel @ Synaptic Bouton Opening

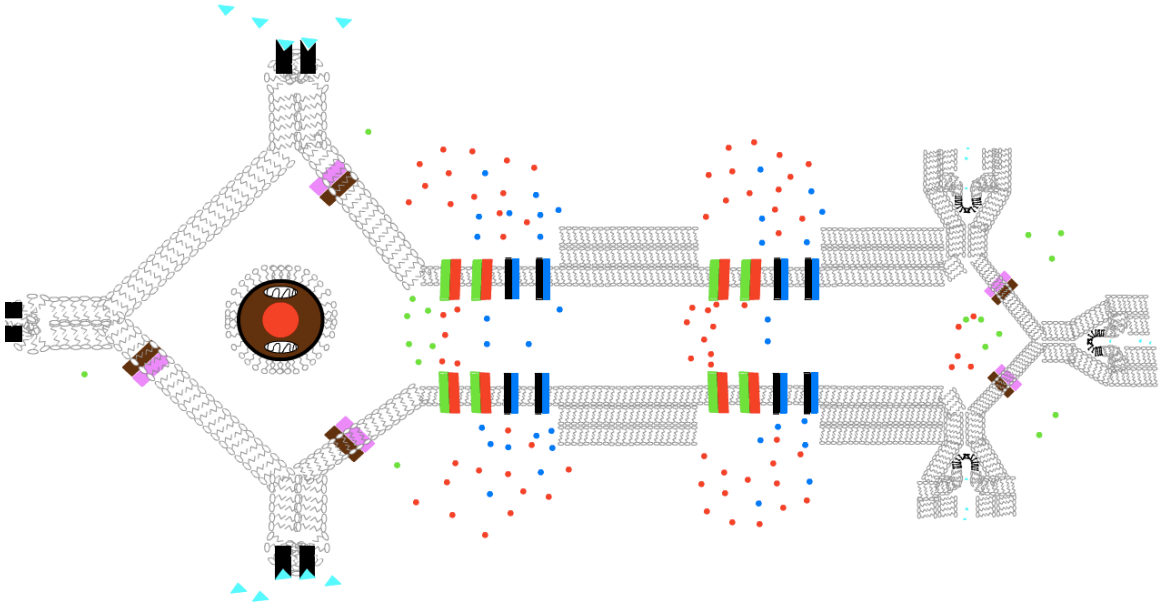





Neuron_Clickable Layers_NEW
File View Control Debug

STEP 5 : Experimental : Cellular : Synaptic vesicle merger and release





Appendix H: Verbal Transcript for Experimental

STRUCTURAL-SUPERFICIAL LEVEL OF NEURON (Wireframe module)

Hi, today we're going to learn about the neuron

Let's go over the basic structures that comprise a neuron by examining this structural model of the neuron

The dendrites are located at these locations,

The calcium channels and ions are located at these locations,

The sodium and potassium channels and ions are located, here, here, here and here,

This entire area is called the axon

And the phospholipids run all along the membrane of the neuron, especially in these rectangles here

The synaptic bouton and synaptic vesicles are located, here, here and here

*Great, now that you have a basic overview of the neuron we will view the cellular model of the neuron and look at these structures in greater detail

BASIC CELLULAR OUTLINE OF THE NEURON

STRUCTURE : Phospholipid

Throughout the neuron are these structures, which are phospholipids.

This is a close up of a phospholipid <point at zoomed phospholipid>

Each phospholipid is comprised of a phosphate head and a tail of carbon and hydrogen that extends from this head.

As you can see these phospholipids form a membrane which surround the neuron <circle along entire neuron>

***Dendrite : Neurotransmitter**

These neon blue structures are neurotransmitters

These black structures are dendrite receptors.

You can see three dendrite receptors here, here and here and the corresponding neurotransmitters,

<play animation>

The first step in the action potential, is that neurotransmitters released from a neuron nearby move towards the dendrite receptors and bind to the dendrite receptors <point to all 3 of them>

STEP 2 : Calcium ions before hillock opening, and Ca+ ions coming towards axon hillock

STRUCTURES :

These green ions are Calcium ions and are positively charged.

This is are calcium channel, as you can see it has two subunits, a pink and brown one <gesture to all 3 of them>

<play animation>

- Once the neurotransmitter binds to the dendrite receptor the Calcium channels in the Neuron open up, here and here, and here, and Calcium ions, which are positively charged enter into the neuron at all three of these locations

- Then these Calcium channels close <point to all three of them>

- The positively charged calcium ions that just entered the neuron thru these calcium channels, begin to move together towards this area here at the start of the axon, right before the first set of sodium and potassium channels, forming a cluster of positive charge

STEP 3 : Action Potential

<point to AP structures>

Here, we see sodium and potassium channels at the top and bottom of the axon

These are Sodium channels, comprised of green and red subunits, at the top and bottom of the axon

These are Potassium channels, comprised of black and blue subunits, at the top and bottom of the axon

These red dots are Sodium ions and are positively charged

The blue dots are Potassium ions, these are also positively charged

- The third step of signal transmission is that the cluster of positive Calcium ions, near the first set of Sodium channels, triggers the Sodium Channels to open, which begins a series of events called the **action potential**.

<start animation>

- First positively charged Sodium ions to enters the axon

- After a while the Sodium channels close
- Then Potassium channels open at the top and bottom of the axon
- As the Potassium channels are opening, the positive sodium ions that entered the axon, start to move along the axon
- Positively charged Potassium ions, now leave the axon, thru the top and bottom Potassium channels
- This balances out the newly entered positive Sodium ions, so the number of positive ions inside the axon, remains the same
- After a while, Potassium channels close
- The positive sodium ions continue to move along the axon,

This is the last step in the action potential

- See how these positive sodium ions can easily pass from one set of Sodium channels to the next set of Sodium channels, because these stacks of phospholipids at the top and the bottom, insulate and prevent these positive ions from leaking outside the axon and the neuron
- Eventually, this cluster of positive Sodium Ions, reaches this second set of sodium and potassium channels and the action potential repeats itself
- The cluster of positively charged Sodium ions, activates the second set of Sodium channels at the top and bottom to open and this allows positive Sodium ions from the top and bottom of the axon to enter the axon
- After a while, these Sodium channels close, like before
- Again Potassium channels at the top and bottom open and positive Potassium ions inside the axon leave the axon thru this channel thru these top and bottom channels
- As this is happening, the positive Sodium ions that came into the neuron from the top and bottom, continues to move along the neuron, just like before, and the Potassium channels, eventually close.
- Again, when the positive Potassium ions leave the axon, this balances out the positive sodium ions that just came in, so the overall number of positive ions, inside the axon, remains the same
- Positive Sodium ions that just entered the neuron, easily move from the second set of Sodium and Potassium channels to the end of the axon
- Like before, this is because there are dense layers of phospholipids at the top and the bottom between this set of Sodium and Potassium channels and the end of the axon, which insulate and prevent these positive Sodium ions from leaking out of the neuron, which is why they can pass so easily, in this space

STEP 4 : Calcium channels at Synaptic Bouton opening

- The cluster of positive Sodium ions activates the Calcium channels here to open
- This triggers the Calcium channels to open and Calcium ions, which are positively charged, to flow into the neuron
- Eventually these Calcium channels close

STEP 5 : Synaptic vesicle merger and release

- Inside each synaptic vesicle are blue neurotransmitter molecules
- Note that each synaptic bouton is covered in phospholipids, each synaptic vesicle is surrounded by phospholipids also.
- So, this concentration of positive calcium ions, causes the phospholipids of the synaptic vesicle to merge with the phospholipids of the synaptic boutons, at each of the synaptic boutons.
- This creates a space for the neurotransmitter inside to exit the neuron
- If a second neuron was nearby these neurotransmitters would bind to the dendrite receptors of this neuron and the entire process we just went thru would repeat again

Appendix I:

SUBCOMPONENTS/ABTSTRACT DATUMS : OVERVIEW :

1. Phospholipids run along membrane/within boxed my. Sheath areas
2. Phosphates made of hydro/carbons
3. Neurotransm. Binds to dendrite
4. Calcium channels open and calcium ions flow
5. Action Potential
6. Synaptic bouton merger
7. Recursive Nature of Signal transmission

APPENDIX J: List of Key Interconnections and their Derivation

CELLULAR-INTERCONNECTIONS/DETAILED DATUMS OVERVIEW :

- Interconnection 1 : Calcium triggers Sodium Channels to open and start AP
    - Are less detailed (control) and detailed (experimental), non-equivalent versions
- Interconnection 2 : Sodium from first AP dissipate and trigger voltage-gated sodium channels of the second action potential to open and cause the 2nd action potential
    - Sub-sub-score : *Explicit re-enumeration of second Action Potential event in axon*
- Interconnection 3 : Myelin Sheath insulates sodium ions from leaking and is comprised of layers of phospholipids <may be explained thru interconnection 4 description>
- Interconnection 4 : The sodium ions which inflow from the second set of action potential channels dissipate along the dense layers of phospholipids which insulate them from leaking en route to Ca+ channels (path must be delineated here)
- Interconnection 5 : Na+ triggers Calcium channels to open (trigger, no path denoted)
    - Are less detailed (control) and detailed (experimental), non-equivalent versions
- Interconnection 6 : Synaptic vesicles are made of phospholipids which insulate the neurotransmitters from leaking
- Interconnection 7 : Synaptic vesicle merges phospholipids with Synaptic Bouton phospholipids during release
- Interconnection 8 : Cluster of positive (.5) Ca+ ions inflowing from synaptic bouton calcium channels cause the synaptic-vesicle-synaptic bouton merger

Appendix K: Experiment 2, Assessment and Grading Rubric

PRETEST :

In 10 sentences, describe the major steps of signal transmission in the neuron, emphasizing the process of the action potential :

Part I :

PLEASE COMPLETE THIS QUESTION **FIRST**, ONCE YOU ARE DONE, **YOU MAY NOT GO BACK TO IT** !

Part A

Please explain the steps of signal transmission in the neuron drawing based upon the instructional materials shown and also any steps not described in the instructional materials that are logically necessary for the process to work and make sense, in the space below on this page and on an additional page if necessary. Please try your best to make references to the *cellular* structures you were shown in the cellular signal transmission videos in your answer and try to write at least 15 sentences, more if possible :

See rubrics for *cell inf. + non-cell inf. below*

SUBCOMPONENTS/ABTSTRACT DATUMS FOR ESSAY GRADING

1. Phospholipids run along membrane/within boxed my. Sheath areas
2. Phosphates made of hydro/carbons
3. Neurotransm. Binds to dendrite
4. Calcium channels open and calcium ions flow
5. Action Potential
6. Synaptic bouton merger
7. Recursive Nature of Signal transmission

{for essay, can use pts. That were stated previously in essay but relevant to grading interconnection in question ; adjectives for points in parentheticals before end of datum unit}

Structural : Wireframe

*locations of various neural structures, explicitly shown in abstract on wireframe [.5]

1. Phospholipids run along membrane/within boxed my. Sheath areas

Phospholipids run along the membrane of the neuron[1] and are concentrated in layers[2] in the myelin sheath areas

2. Phosphates made of hydro/carbons

Each phospholipid is comprised of a phosphate head[.5] and a tail that extends from this head [.5] of carbon[1] and hydrogen[1]

3. Neurotransm. Binds to dendrite

Neurotransmitters released from a neuron nearby[1] move towards the dendrite receptor[1] and bind to the dendrite receptor[1]

4. Calcium channels open and calcium ions flow

Calcium channel, has two subunits[1], a pink one[.5] and brown[.5] one.

Once the neurotransmitter binds to the dendrite receptor[1] the Calcium channels in the Neuron open up[1] and positive[.5] Calcium ions flow into the neuron[1]

Then these Calcium channels close[1]

5. Action Potential

Sodium channels open[1] and Positively charged[.5] Sodium enters the axon[1]

After a while, these Sodium channels close[1]

Potassium channels open[1] and positive[.5] Potassium ions[1] inside the axon[.5] leave the axon thru this channel thru these channels

As this is happening[1], the positive[.5] Sodium ions[1] that came into[.5] the neuron from the channels[1], continues to move along the neuron[1], and the Potassium channels, eventually close[1]

When the positive[.5] Potassium ions leave the axon[1], this balances out the positive sodium ions that just came in[1.5], so the overall number of positive ions, inside the axon, remains the same[1]

This is the last step in the action potential[1]

6. synaptic bouton merger

The synaptic vesicle, a membrane of spheres which blue contain neurotransmitter molecules[2], mergers with the synaptic bouton[2], and creates an opening for neurotransmitter to exit the neuron[1.5]

7. Recursive Nature of Signal transmission

If a second neuron was nearby these neurotransmitters[1] would bind to the dendrite receptors of this neuron[2] and the entire process we just went thru would repeat again[1.5]

CELLULAR-INTERCONNECTIONS/DETAILED DATUMS OVERVIEW:
FOR ESSAY GRADING

- Interconnection 1 : Calcium triggers Sodium Channels to open and start AP
- Interconnection 2 : Sodium from first AP dissipate and trigger voltage-gated sodium channels of the second action potential to open and cause the 2nd action potential
    - Sub-sub-score : *Explicit re-enumeration of second Action Potential event in axon*
- Interconnection 3 : Myelin Sheath insulates sodium ions from leaking and is comprised of layers of phospholipids <may be explained thru interconnection 4 description>
- Interconnection 4 : The sodium ions which inflow from the second set of action potential channels dissipate along the dense layers of phospholipids which insulate them from leaking en route to Ca+ channels (path must be delineated here)
- Interconnection 5 : Na+ triggers Calcium channels to open (trigger, no path denoted)
- Interconnection 6 : Synaptic vesicles are made of phospholipids which insulate the neurotransmitters from leaking
- Interconnection 7 : Synaptic vesicle merges phospholipids with Synaptic Bouton phospholipids during release
- Interconnection 8 : Cluster of positive (.5) Ca+ ions inflowing from synaptic bouton calcium channels cause the synaptic-vesicle-synaptic bouton merger

Cell Inf. {for essay, can use pts. That were stated previously in essay but relevant to grade interconnection in question ; adjectives for points in parentheticals before end of datum unit}

***Anytime mentions Top or Bottom Sodium or Potassium Channels = .5 for each (.5 for T, .5 for B)**

1. Calcium triggers Sodium Channels to open and start AP

Model Answer :

Positive[.5] calcium ions entering the neuron[1] from the (three) calcium channels[.5] near the dendrites of the neuron[.25], flow together along the pre-axon (Soma) area of the neuron[1.5], and form a cluster (converge) together[2] of positive charge[1] near the first set of sodium and potassium channels[1], which triggers the top[.25] and bottom[.25] sodium channels to open[1] starting the process of the action potential[.5].

2. Sodium from first AP dissipate and trigger voltage-gated sodium channels of the second action potential to open & cause 2nd action potential

Model Answer :

Positively charged[.5] Sodium ions[1] which flow into the neuron from Sodium channels[1] at the top[.5] and bottom[.5] of the neuron flow from one set of Sodium/Potassium channels[1.5], thru a dense layer of phospholipids[2] at the top[.5] and bottom[.5] of the neuron which insulate these Sodium ions from leaking[1.5], and form a cluster of positive[.5] charge[2] before the second set of Sodium and Potassium channels[1.5], triggering the second set of Sodium channels[1] at the top[.5] and bottom[.5] to open, and causing positive[.5] Sodium ions[1] to inflow[1] from the top[.5] and bottom[.5] of this second area, initiating the action potential again[1.5]

*Sub-sub-score : *Explicit re-enumeration of second Action Potential event in axon**

- After a while, these Sodium channels close[1]
- Again Potassium channels at the top[.5] and bottom[.5] open[1] and positive[.5] Potassium ions[1] inside the axon[.5] leave the axon thru this channel thru these top[.5] and bottom[.5] channels
- As this is happening[1], the positive[.5] Sodium ions[1] that came into[.5] the neuron from the top[.5] and bottom[.5] channels[1], continue to move along the neuron[1], and the Potassium channels, eventually close[1]
- Again, when the positive[.5] Potassium ions leave the axon[1], this balances out the positive sodium ions that just came in[1.5], so the overall number of positive ions, inside the axon, remains the same[1]

3. Myelin Sheath insulates sodium ions from leaking and is comprised of layers of phospholipids

Model Answer :

This is a dense layer of stacked[1.5] phospholipids[2] at the top[.5] and bottom[.5] of the neuron, which insulates[1.5] positive[.25] sodium ions from leaking[1]

4. The sodium ions which inflow from the second set of action potential channels dissipate along the dense layers of phospholipids which insulate them from leaking

Model Answer :

The sodium ions which inflow[1] from the second set of action potential channels[2] dissipate along the dense layers of phospholipids[2] which insulate them from leaking[2] outside the axon[.5]

5. Na+ triggers Calcium channels to open

Positive[.5] sodium ions[1] from the 2nd action potential Na+ channels[2] at the top[.5] and bottom[.5] form a *cluster of positive[.5] charge[1]* and reach the end of the axon[1.5] and trigger the Calcium channels to open[1] and allow positively[.5] charged Calcium ions to flow into the neuron[1], which eventually close[.5]

6. Synaptic vesicles are made of phospholipids which insulate the neurotransmitters from leaking

Model Answer :

The synaptic vesicle is comprised of phospholipids[2] which insulate the neurotransmitters[1] from leaking into the synaptic bouton[1]

7. Synaptic vesicle merges phospholipids with Synaptic Bouton phospholipids during release

Model Answer :

Positively[.5] charged Calcium ions[1] <versus merely the Calcium channel opening in control> cause the synaptic vesicles made of phospholipids[2], to merge[1.5] with the phospholipids of the synaptic vesicles[2], at each of the synaptic bouton locations[.5], creating an opening for neurotransmitters to be released at these locations[1]

8. Cluster of positive_Ca+ ions inflowing from synaptic bouton calcium channels cause the synaptic-vessicle-synaptic bouton merger

Model Answer :

Cluster of positive[.5] Ca+ ions[2] inflowing from synaptic bouton calcium channels[1] cause the synaptic-vessicle-synaptic bouton merger[1]

Part II :

DIRECTIONS : *VERY IMPORTANT, YOU CANNOT RETURN TO A QUESTION ONCE YOU'VE ANSWERED IT, THE END OF THE TEST GIVES AWAY THE BEGINNING, SO ONCE YOU ANSWER AND QUESTION AND MOVE ON, NEVER WORK ON THE QUESTION AGAIN (THIS APPLIES FOR ALL 17 SHORT ANSWER QUESTIONS BELOW)

PART A :

Please write 2-3 sentences for each of the free response questions below, in the space below each question, ***emphasizing cellular structures and terminology (such as phospholipids)*** *you've learned in the videos in your answers :*

1. Explain why neurotransmitter doesn't leak from synaptic vesicles into the synaptic bouton (in terms of cellular structures) :

The synaptic vesicle is comprised of phospholipids[2, *mandatory for any credit*] which insulate the neurotransmitters from leaking[1.5] into the synaptic bouton[1]

- **no non-inf version**

2. Describe what triggers calcium channels to open at the synaptic bouton, located at the end of the neuron :

Positive[.5] sodium ions[1] from the 2nd action potential Na+ channels[2] at the top[.5] and bottom[.5] form a *cluster of positive[.5] charge[1]* which dissipate along the dense layers of phospholipids[2] which insulate them from leaking[2] outside the axon[.5] and reach the end of the axon[1.5] and trigger the Calcium channels to open[1] and allow positively[.5] charged Calcium ions to flow into the neuron[1]

- Non-Inf Version : Action Potential triggers Ca+ channels to open [2]

3. Describe the process of the synaptic vesicle merging with the synaptic bouton in terms of cellular structures, prior to neurotransmitter release :

Concept of phosphates merging must be present for there to be any credit awarded

Positively[.5] charged Calcium ions[1] cause the synaptic vesicles made of phospholipids[2], to merge[1.5] with the phospholipids of the synaptic vesicles[2], at each of the synaptic bouton locations[.5], creating an opening for neurotransmitters to be released at these locations[1]

- **no non-inf version**

4. Describe what triggers the FIRST set of sodium and potassium channels located RIGHT AFTER the dendrites to open (action potential) and how clustering is involved in the process of it triggering the channels to open here :

Positive[.5] calcium ions entering the neuron[1] from the (three) calcium channels[.5] near the dendrites of the neuron[.25], flow together along the pre-axon (Soma) area of the neuron[1.5], and form a cluster (converge) together[2] of positive charge[1] near the first set of sodium and potassium channels[1], which triggers the top[.25] and bottom[.25] sodium channels to open[1]

- Dendritic signals[1] mediated by Calcium[2] are integrated right before the first set of charge gated sodium channels[1], opening them[1]

5. Describe what triggers the action potential (channel openings) at a SECOND set of sodium and potassium channels that are located after a first set of sodium and potassium ions and how it arrives at the second set of sodium and potassium channels and where it comes from :

Positively charged[.5] Sodium ions[1] which flow into the neuron from Sodium channels[1] at the top[.5] and bottom[.5] of the neuron flow from one set of Sodium/Potassium channels[1.5], thru a dense layer of phospholipids[2] at the top[.5] and bottom[.5] of the neuron which insulate these Sodium ions from leaking[1.5], and form a cluster of positive[.5] charge[2] before the second set of Sodium and Potassium channels[1.5], *triggering the second set of Sodium channels*[1] at the top[.5] and bottom[.5] to open, initiating the action potential again[.5]

- Non Inf Version <taken from control transcript> Positive[.5] Sodium ions[1] that previously entered the axon thru the first action potential event[1.5], dissipate along the axon[2], generating action potentials further along the axon[2.5]

6. Describe the structure present in the axon between one set of Sodium and Potassium channels and a second set of Sodium and Potassium channels, called a myelin sheath, and what function it serves :

This is a dense layer of stacked[1.5] phospholipids[2] at the top[.5] and bottom[.5] of the neuron, which insulates[1.5] positive[.25] sodium ions from leaking[1] outside the neuron [1] as they flow from one set of sodium and potassium channels to the next[1.5]

- **no non-inf version**

PART B :

7. What would happen to signal transmission if Calcium ions were negatively charged instead of positively charged :

Most Proximal Causal Effects Conc. Int Version :

Calcium ions would still inflow into the neuron[1], congregate[1] and move towards each other in the dendrite area before the first set of the Na/K Channels,[2] but now, there would be a cluster of negative charge[1.5], and this would prevent the first set of Sodium channels at the top[.5] and bottom[.5] of this area from opening[2] and would prevent channels Sodium ions from inflowing into the neuron[1] from the top[.5] and bottom[.5] Na+ channels[1], and thus block the action potential from propagating[2]

8. Describe what would happen if the amount of phospholipid was reduced in the area between the first set of Sodium and Potassium channels and second set of Sodium and Potassium channels :

Most Proximal Causal Effects Conc. Int Version :

Positive[.5] Sodium ions which inflow from the first set of Na/K channels[1] would not be insulated well from the top[.5] and bottom[.5] areas of the space in between Na/K channels[1], and would leak outside of the neuron[2]

Hence, not enough positively[.5] charged Sodium ions would cluster[2] and reach the second set of Na/K channels,[2] and Sodium channels would not open here[1] and hence the action potential would not begin here (at this 2nd set of Na/K channels)[1.5]

9. Describe what would happen to the signal transmission process if the sodium channels at the second set of action potential channels were blocked from opening :

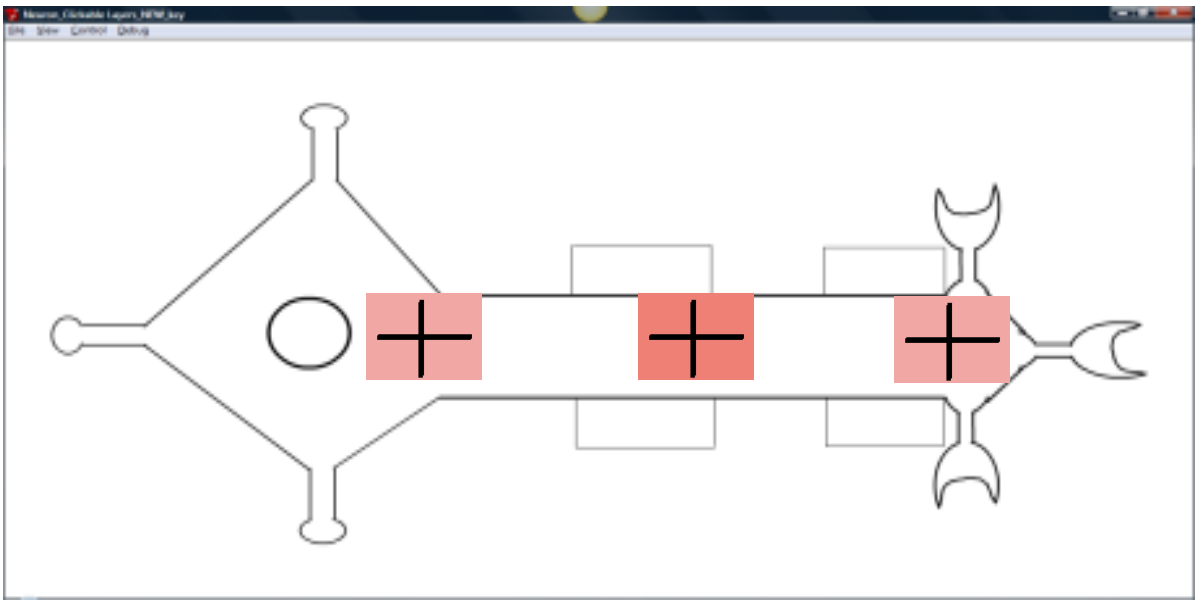
Most Proximal Causal Effects Conc. Int Version :

Positive[.5] Sodium ions[1] would not inflow into the axon[1] from the top[.5] and bottom[.5] of the neuron, potassium channels would still open[1] and positive[.5] potassium ions would exit the neuron[1] from the top[.5] and bottom[.5], hence the inside of the membrane would have a net negative net charge[2]. No positive[.5] sodium ions[1] would flow thru the stacks of phospholipids[2] between this 2nd set of Na/K channels at the end of the axon[1.5], and hence the Calcium channels near the synaptic bouton[1] would not open[1], the synaptic bouton and vesicles would not merge[1.5] phospholipids[2], and neurotransmitter would not be released[2]

PART C : Please answer the following 5 drawing questions :

Use the drawing tools of MS Word to fill in the questions below :

1. On the wireframe model below, please copy and paste the plus ("+") sign below at each location in the neuron where a concentration of positive charges triggers a channel(s) to open :

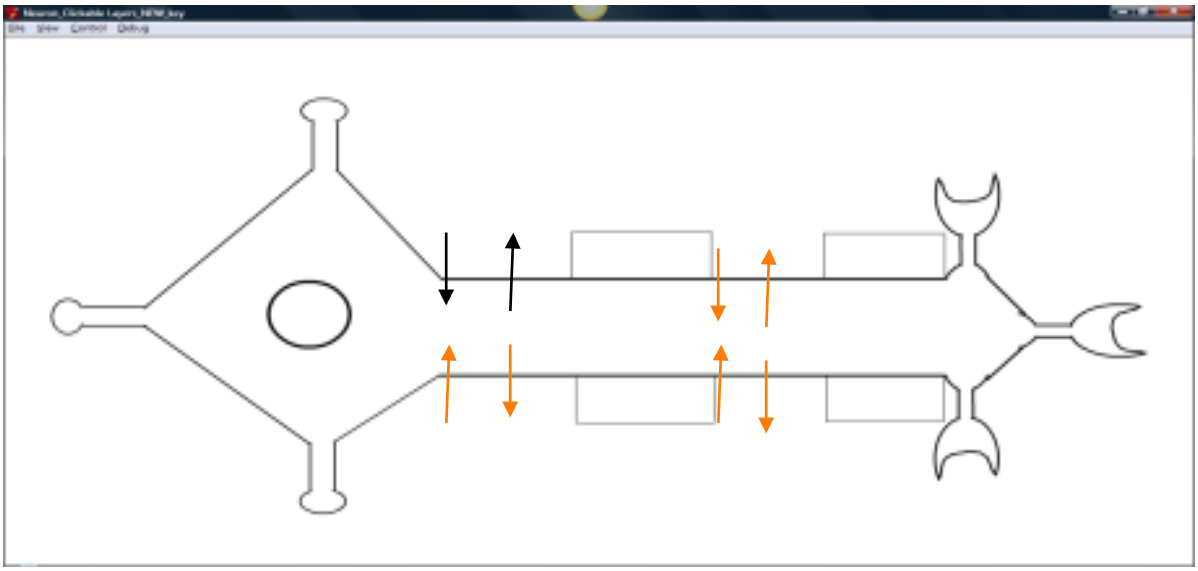


Black = shown explicitly in both conditions

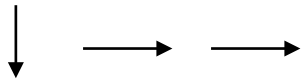
orange = shown in "abstract" location on wireframe

red = requires mental animation

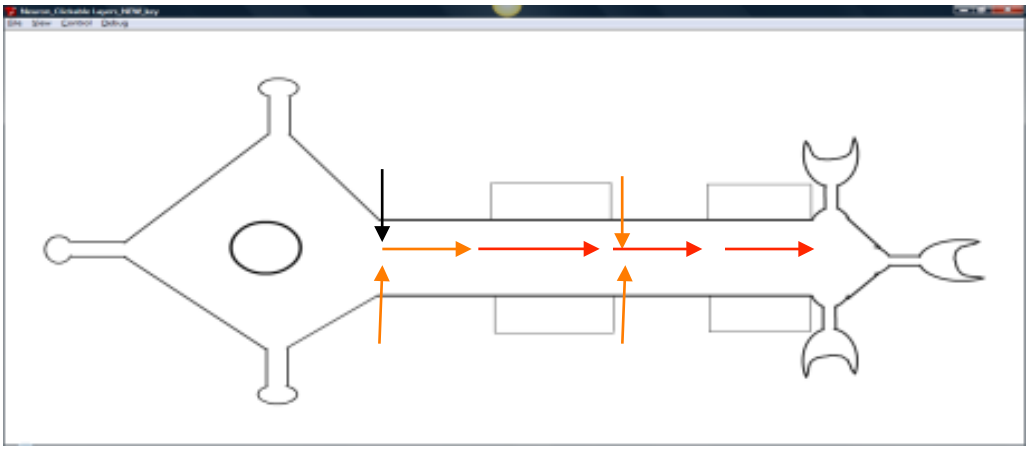
2. On the wireframe model below, please draw arrow(s) from the outside of the neuron to the inside to denote the locations where sodium ions enter the neuron, and arrow(s) from the inside of the neuron pointing to the outside to denote locations where Potassium ions exit the neuron



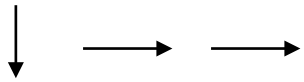
3. On the wireframe model below, please draw a series of arrows



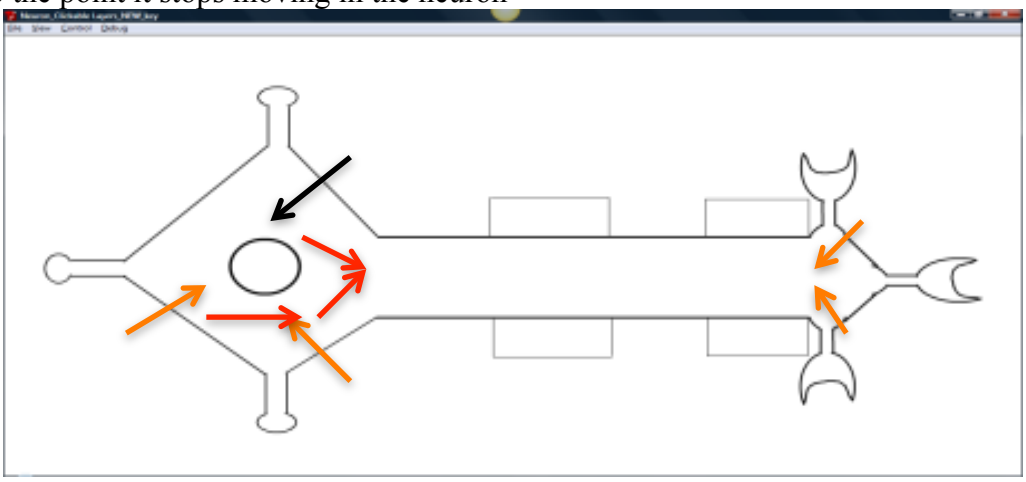
to show the path(s) of sodium from the point it first enters the neuron (from all points of entry) to the point it stops moving in the neuron



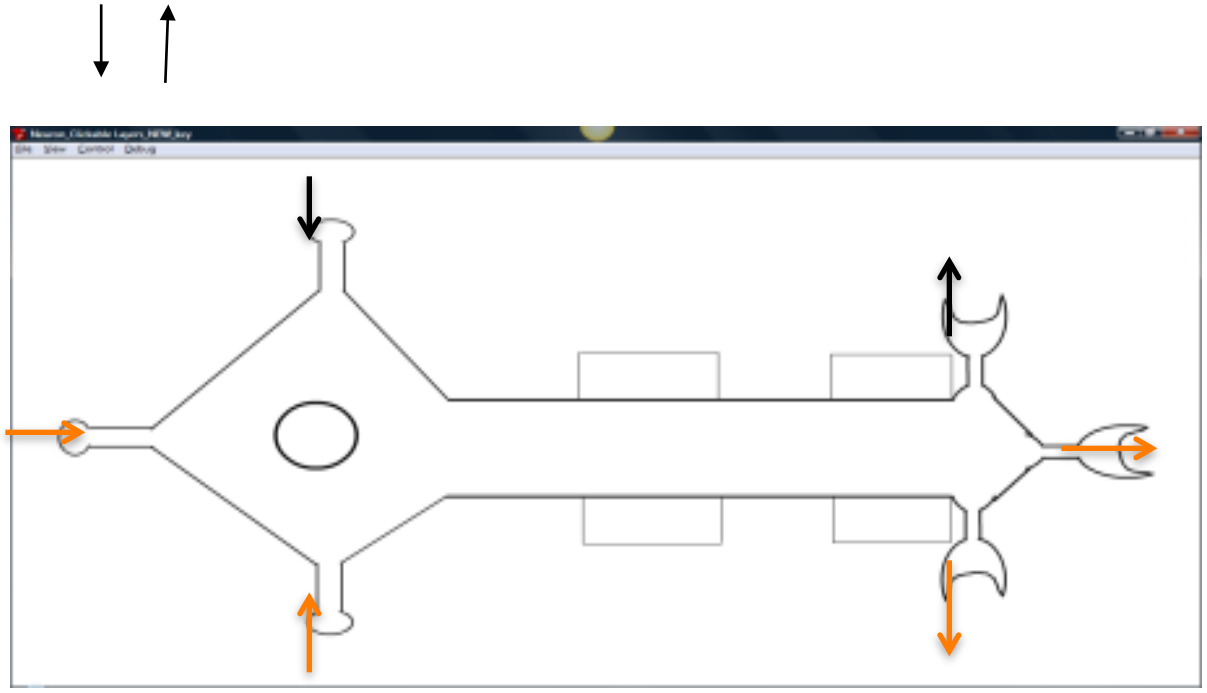
4. On the wireframe model below, please draw a series of arrows



to show the path(s) of calcium from the point it first enters the neuron (from all points of entry) to the point it stops moving in the neuron



5. On the wireframe model below, please use arrows to mark where neurotransmitter binds to dendrite and where synaptic vesicles release neurotransmitter :



SURVEY QUESTIONS (MANDATORY)

Please notify the experimenter when you are starting this survey section

PLEASE ANSWER THESE BIOGRAPHICAL QUESTIONS BELOW AFTER FINISHING THE EXAM :

Gender :

Undergraduate Major :

Graduate Major :

Please bold the correct choice below for each of the following multiple choice questions :

1. The last time I took a course that taught concepts about the neuron and action potential was:

   A. Never

   B. High School

   C. College

   D. Graduate School

2. In college and/or graduate school I took the following number of courses that taught concepts related to the neuron and action potential

   A. 0
   B. 1
   C. 2-3
   D. More than 3

3. I have taken/am taking a Neuroscience Course of some sort (Example : Brain and Behavior I or II) at TC :

   A. YES

   B. NO

Please notify the experimenter when you are finished with this survey section

THANKS SO MUCH FOR YOUR PARTICIPATION ☺