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CASE STUDY
Phantom Limb Pain: Feeling Sensation from a Limb that is No Longer Present and What it Can Reveal About Our Brain Anatomy

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This is a flexible, interrupted video case that uses phantom limb pain as a platform to investigate brain anatomy with a focus on somatosensory cortical mapping and the homunculus. The case begins with a video of neurologist Dr. V.S. Ramachandran interviewing two amputees who experience phantom limb pain (part one). Through Dr. Ramachandran's dialog with amputees, students learn about the paradoxical condition of feeling pain in a limb that does not exist (e.g., phantom limb pain). Students witness Dr. Ramachandran analyzing fMRI data from an amputee, and subsequently learn the somatosensory cortical mapping of the amputee has remarkably changed. Dr. Ramachandran also introduces and demonstrates one form of treatment for phantom limb pain, the mirror box. The video case is supplemented with optional opportunities for further exploration about the mirror box (part two) and somatosensory cortical mapping, via the two-point discrimination test (parts three and four). In part two, students use the primary literature to investigate the effectiveness of the mirror box, and practice skills of interpreting figures. In parts three and four, students conduct a two-point discrimination test (part three) on each other or a person in their residence and analyze class data (part four). Students are led to discover conceptual connections between all four parts of this module. As one example, students are challenged to predict how two-point discrimination data from amputees (interviewed in the video, part one) would compare to students' two-point discrimination data (parts three and four). While the four parts of this learning module are highly interconnected, instructors can choose to selectively implement one or more parts. In addition, each part can be executed in the face-to-face classroom, as out-of-classroom assignment, in a synchronous or non-synchronous video meeting platform, or as a hybrid of these options, providing flexibility for the instructor. This case has been used in a 100-level face-to-face, non-science major course and it has been modified as an online module for a 300 level *General Physiology* course.

Key words: phantom limb pain, phantom limb syndrome, homunculus, somatosensory cortex, somatosensory cortical mapping, two-point discrimination test, two-point discrimination threshold, mirror box, mirror therapy, video case

CONTEXT

Case studies employ a story to educate (Herreid, 1997) and many cases originate from a written narrative, however some case studies use videos (Pai, 2014; Prud'homme-Généreux et al., 2019), such as the one described here. Video based stories can provide opportunities for students to witness a person, such as a patient, or an amputee in this case, and observe a person's behavior while listening to his/her narrative. For example, in this video case, we witness neurologist Dr. Ramachandran examine Derek, who has had part of his arm amputated. During this examination, we watch Dr. Ramachandran stroke Derek's cheek, and we are surprised to hear Derek report that he feels a stroking sensation on his cheek *and* on his phantom (amputated) limb. This instantly raises the question, "Why does Derek feel sensation on his phantom arm while Dr. Ramachandran strokes his cheek?" Witnessing Derek's curious response to Dr. Ramachandran's test is captivating, and we follow Dr. Ramachandran as he investigates this surprising finding.

This video also provides footage that helps "normalize" a person who is considered disabled. In this video, we watch Derek fixing his car, playing pool, and teaching Dr. Ramachandran how to golf. These observations provide specific examples of the abilities of a person who is considered disabled and can stimulate reflections about this label. Also, this video can evoke feelings of personal connection and empathy while listening to Derek and James (another amputee) describe their respective accidents that led to amputation and subsequent phantom limb pain. Lastly, this learning module offers three optional learning activities that propel students to delve further into phantom limb pain and brain anatomy. Students transition from being a video observer to an active participant by employing methods of self-relevancy and elaboration.

This case employs self-relevancy, elaboration, and active learning methods to stimulate curiosity and enduring learning. Dr. Sarah Cavanagh describes the effectiveness of self-relevant activities in her book, *The Spark of Learning, Energizing the College Classroom with the Science of Emotion* (Cavanagh, 2016). Self-relevant activities are ones that make course concepts relevant to life outside the classroom and can include a hands-on approach for students to experience course material. The case described here offers connections to life by teaching about somatosensory cortical mapping (and the term, homunculus) via an extraordinary syndrome, phantom limb pain. While my students, fortunately, have not experienced this syndrome themselves, most all of them have heard about it and are curious to learn how a person can feel pain in a limb that is not physically present. Rather than starting a lesson with, "a somatosensory cortical map is…."or "a homunculus is….", this case begins with a video about amputees who experience phantom limb pain, and as students learn more about possible underlying causes of this curious syndrome, they are introduced to a somatosensory cortical map/homunculus, as well as how it may change in an amputee. Secondly, this case uses self-relevancy by employing a hands-on approach. Students actively engage in this lesson by conducting a two-point discrimination test on each other (or on a volunteer at home), thus students are not passive observers in this lesson. Students also analyze class data and make inferences from class trends.

This learning module also employs elaboration, "the process of finding additional layers of meaning in new material," as described in *Make it Stick, the Science of Successful Learning* (Brown et al., 2014). Elaboration is used in this case when students are challenged at the end of the case to connect their understanding of a somatosensory cortical map and the term, homunculus (terms covered in the first part of the case) to data from a two-point discrimination test (parts 3 and 4 of the case). Students revisit their initial understanding of a somatosensory cortical map and view it from a different perspective. They are asked to speculate why certain body regions occupy large areas within the map, a question not posed earlier in the case. Students are also asked to predict trends of two-point discrimination data from an amputee with an altered somatosensory cortical map, shown in part one. Lastly, students consider if the relative size of a body region within the somatosensory map/homunculus shares a relationship to data collected from a two-point discrimination test. Through this learning module, students engage in self-relevant activities, and learn by elaboration and experimentation. Student materials and implementation notes are available from the corresponding author or from cases.at.june@gmail.com.

Course Overview

This case was originally designed for and implemented in an undergraduate, lower-level non-science major course, *Matters and Mysteries of Your Brain*. This course enrolls up to 20 students per section, ranging from freshmen to seniors. Most students enroll in this class to complete a core curriculum requirement. The majority of students are taking this course out of necessity rather than by choice, and it can be challenging to motivate and excite students in this class. Many students have previously convinced themselves that they are not "good" at science or that science is not applicable to "real life". To address this student-motivation challenge, this case was designed to promote: 1) curiosity about science by exploring phantom limb pain and ways to treat pain from a limb that does not exist, 2) engagement via student experimentation using a two-point discrimination test, and 3) connectivity between phantom limb pain, brain anatomy (more specifically the somatosensory cortical map), and the two-point discrimination test.

During the COVID-19 pandemic, this case study was modified and executed as an online module for an upper-level biology course for science majors, *General Physiology*, that enrolls up to 40 students per lecture section. The majority of students in this class are biology majors, health science majors, and neuroscience majors, many of whom desire to build a career in the health professions. This case served well as an introduction to the swift, unexpected change to online learning. The case's connectivity to "real life" coupled with experiential, activity-based learning helped ease anxiety and build student (and instructor) confidence in this new online learning platform. Students reported feeling that this case helped promote a sense of connectivity to "real life" and to class at a time when many felt abruptly disconnected. And, while the academic rigor of this case was originally lower than previous face-to-face assignments in *General Physiology*, it did provide time for problem-solving technical challenges that accompanied the swift transition to online learning. In the future, the rigor of this case will be enhanced for this upper-level biology class, as described below.

Case Overview

This case takes a multi-pronged approach to promote enduring learning via 1) exploration of phantom limb pain through a video interview of amputees who suffer from this condition, 2) interpretation of primary literature to explore treatments of phantom limb pain, 3) experimentation with the two-point discrimination test and 4) data analysis. This flexible, four-part module provides interconnectivity between its separate parts, and builds a deeper understanding about the somatosensory cortical map (also referred to as the somatosensory homunculus) and phantom limb pain, in addition to enhancing skills of data analysis.

Case Management

This is a flexible, four-part interrupted learning module. Instructors can choose to use one or more parts, and instructors can choose to implement parts in the face-to-face classroom, an asynchronous online class, a synchronous online class, an out-of-classroom assignment, or a hybrid approach. Combinations that have been successful are described in the implementation notes.

Part one begins with students viewing the first 16 minutes of a freely available video by NOVA, *Secrets of the Mind*, that that follows neurologist Dr. Ramachandran as he interviews two amputees who experience phantom limb pain. During this video, students are briefly exposed to the concept of a homunculus and to one form of treatment for phantom limb pain, the mirror box. Students work individually or in groups to answer instructor-provided questions that follow the same order as information is presented in the video. Questions highlight the main points of the video, guide students to research the term, "somatosensory homunculus," and lead students to make connections between phantom limb pain, the homunculus, and somatosensory cortical mapping. Knowing the instructor-provided questions match the order of content presentation within the video, students are encouraged to pause the video to fully answer questions or possibly re-watch a segment. Previous studies suggest using instructor-set pause points between sets of questions (Prud'homme-Généreux et al., 2019), and this may prove helpful in this video case as well. Pause points are included in the student handout to provide that option for those wish to implement this technique. Lastly, a low stakes quiz is administered at the end of part one to motivate students to thoroughly complete this assignment.

Part two challenges students to interpret a figure from a primary science article (Foell et al., 2014) focused on mirror therapy for phantom limb pain. Initially, the students are solely provided with Figure 4 from this article. Students remain blinded to the rest of the article and are led, through a series of questions, to extract information from the figure and to list of "need to know" questions that would help them better understand the graph. Then, students are presented with the abstract, and they are challenged to use the abstract to better interpret the figure and, if possible, to answer students' "need to know" questions posed earlier. Students are asked to generate a second list of "need to know" questions that would allow them to better understand the study. Towards the end of this unit, students are provided with the entire article and are challenged to answer their previously listed "need to know" questions. Lastly, students are asked to describe what experiments they would plan next if he/she/they were authors on this paper.

Parts three and four engage students to conduct a two-point discrimination test on a partner (part three) and challenges students to analyze class data and draw conclusions (part four). Importantly, during this final unit, students are led to make connections between the two-point discrimination test (parts three and four), and somatosensory cortical maps (aka the homunculus, part one). This provides opportunities for deeper reflections of the conceptual connectivity of the entire case and promotes enduring learning via interleaving of concepts. Another low stakes online quiz was completed at the end of this unit. Assessment was also measured by student performance on questions posed on a higher stakes exam at the end of the semester.

Learning Objectives

By the end of this module, students should achieve the following objectives. Content objectives are labeled with a letter "C" and skill objectives are labeled with an "S". In parentheses are the parts of the case that align with each learning objective.

1. Define phantom limb pain and explain one method used to alleviate this type of pain. C (part one)
2. Sketch a body map on the somatosensory cortex (e.g., homunculus) and explain how one amputee's somatosensory cortical body map changed. C (part one)
3. Interpret a line graph, distinguish data groups, and describe conclusions that can and cannot be drawn from data shown. S (part two)
4. Propose ideas of future experimentation that build on published data. S (part two)
5. Perform a two-point discrimination test and measure the minimum two-point discrimination threshold. S (part three)
6. Construct a bar graph that displays mean data. Graph includes correct axes labels. S (part four)
7. Interpret data from a two-point discrimination test and draw conclusions about which body parts have more sensory receptors. S (part four)
8. Predict which body parts have greater representation in the somatosensory cortex based on two-point discrimination threshold values. S (part four)
9. Describe relationships between two-point discrimination threshold values, density of sensory receptors, and relative size of body regions within the somatosensory homunculus. C (part four)

CASE EVALUATION

Assessment Overview

Student learning was assessed via two low stakes quizzes and on questions posed on a higher stakes exam. Low stakes quizzes were announced in advance and executed in a timed, open-book format, allowing students to refer to their completed worksheets during the quiz. Prior to the quiz, students were informed that the quizzes were timed and there was not enough time to re-watch the video or re-read the article. This was done to motivate students to thoroughly complete worksheets, and in the case of the COVID-19-induced transition to online learning, to lower anxiety associated with the abrupt change in learning modality. Students were informed that these low stakes quizzes were practice for a higher stakes exam at the end of the semester. The concept of "learning from our mistakes" was a theme that was already in place for *General Physiology*. The opportunity to learn from mistakes on a lower stakes quiz and to demonstrate that learning on a higher stakes exam, was heavily emphasized throughout the semester. Examples of selected questions from online quizzes administered to sixty-eight students in *General Physiology* are listed in Table 1. The first two questions in Table 1 are multiple selection (not multiple choice) style questions. For multiple selection questions, students must select all correct answers not simply the single best answer, which is more challenging. The percentage of students who selected each answer are shown in right column of Table 1. The answer key is provided in the implementation notes, which are available upon request from the corresponding author. The class average grade was higher than previous quizzes in *General Physiology*, presumably due to the open book and lower academic rigor of this case for this upper-level biology class. Suggestions to increase academic rigor for a 300-level science major course are provided below.

Student feedback

Surveys were given to students after the case was executed as an online module, prior to knowledge of their grades. Fifty-three *General Physiology* students completed the post-case survey and their responses are reported in Table 2. Using a Likert scale, students rated their responses to statements listed in Table 2. Students were asked to report using the following scale: 1 = Strongly Disagree, 2= Disagree, 3=Neither Agree nor Disagree, 4=Agree, 5= Strongly Agree.

This survey (Table 2) and quiz scores (Table 1) suggest that students gained understanding about the somatosensory cortex, homunculus, phantom limb pain, and

Question	Percent students who selected each answer (in blue)
Which of the following statements is/are supported by Derek's brain imaging data? (select ALL correct answers) _Derek's brain, like other human brains, is not capable of change. _In Derek's brain, the area representing the left cheek has expanded into space that was previously represented by the left hand. _the part of the brain that receives input from the face is adjacent to the part that receives input from the leg.	Which of the following statements is/are supported by Derek's brain imaging data? (select all correct answers) _Derek's brain, like other human brains, is not capable of change. (0%) _In Derek's brain, the area representing the left cheek has expanded into space that was previously represented by the left hand. (98.6%) _the part of the brain that receives input from the face is adjacent to the part that receives input from the leg. (1.5%)
The mirror box can provide relief to some patients with phantom limb syndrome by…(select ALL correct answers) _Tricking the patient to temporarily think his/her phantom limb has regenerated. _Providing visual signals to the brain that causes the phantom hand to become further clenched. _Providing visual feedback that can lead to decreased clenching in the phantom hand.	The mirror box can provide relief to some patients with phantom limb syndrome by…(select all correct answers) _Tricking the patient to temporarily think his/her phantom limb has regenerated. (5.88%) _Providing visual signals to the brain that causes the phantom hand to become further clenched. (0%) _Providing visual feedback that can lead to decreased clenching in the phantom hand. (94.12%)
Which area of the body has the largest two-point discrimination distance? (select the single best answer) _Back of hand _Back of neck _Fingertip	Which area of the body has the largest two-point discrimination distance? (select the single best answer) _Back of hand (1.47%) _Back of neck(92.65%) _Fingertip (5.88%)
Which area of the body has the highest density of receptors in the skin? (select the single best answer) _Back of hand _Back of neck _Fingertip	Which area of the body has the highest density of receptors in the skin? (select the single best answer) _Back of hand (0%) _Back of neck (0%) _Fingertip (100%)
Which area of the body has the largest representation in the homunculus? (select the single best answer) _Back of hand _Back of neck _Fingertip	Which area of the body has the largest representation in the homunculus? (select the single best answer) _Back of hand (1.47%) _Back of neck (4.41%) _Fingertip (94.17%)

Table 1. Example quiz questions and accompanying student scores.

the two-point discrimination test. Most students agreed the two-point discrimination test helped make connections between class material and daily life. And the majority of students (53% = sum of strongly disagree and disagree) reported they would *not* prefer a lecture to the teaching format described here, suggesting that this video case was a more attractive learning platform for most students. During synchronous online meetings, the instructor asked for additional open-ended feedback about the case study. Students shared that this case teaching approach was helpful during the online transition in part because it was not overwhelming and because they interacted with a member in their household to complete the two-point discrimination test. And, while students appreciated that the first online module was not overly taxing, students also noticed that the level of detail was not as high as it was for pre-pandemic, face-to-face activities. This comment is consistent with the original design of this case for a 100 level non-science major course. Suggestions for increased rigor are described below.

When this case was executed in a non-science major course, students shared their reflections in an open-ended, anonymous survey. The non-science majors shared that they found the video about phantom limb pain to be intriguing, and they were grateful for class discussion following the video to more slowly dissect the fMRI data that Dr. Ramachandran showed in the video. Students enjoyed the hands-on approach of the two-point discrimination test. Some had reported doing the test before but had not fully understood what the data revealed. After this module, they better understood the test and the data generated by the test. Interestingly, some students raised many questions about variables that could impact the data, such as handedness, previous injury, etc. This discussion led to an impromptu continuation of the experiment where students designed and tested if those variables could impact data. To this instructor, it was rewarding to witness experimentation continue due to student interest and curiosity.

Future Directions

There are many options for further enrichment and increased academic rigor. Some of these options were inspired by students and are listed below.

Semi-Independent Project

After students execute two-point discrimination tests (part three) and analyze data (part four), they can design an experiment to test if a variable (such as handedness,

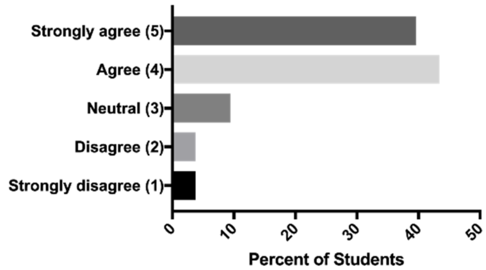
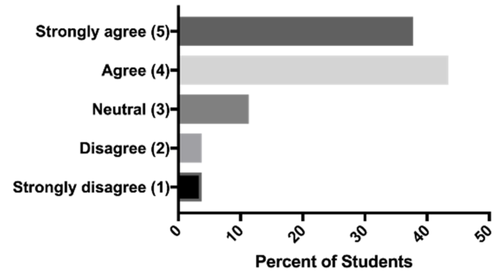
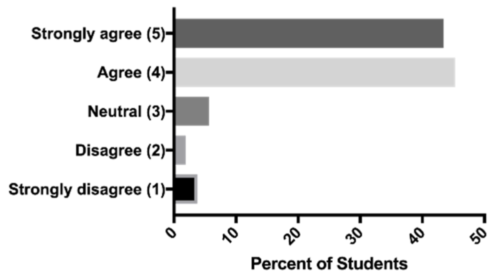
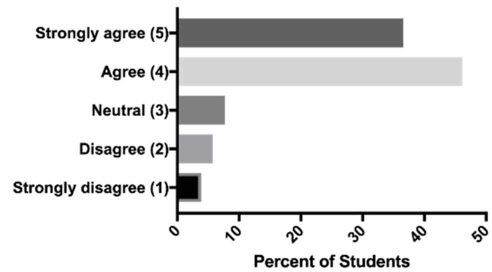
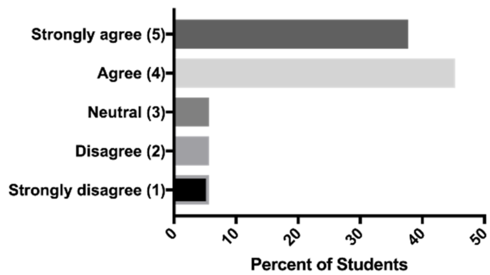
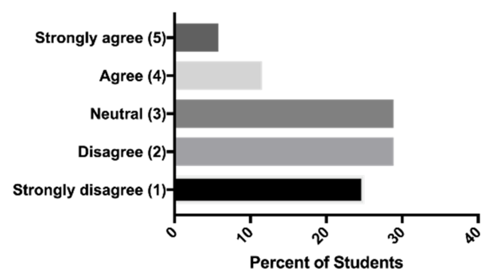
Survey statement/ AVE score	Student responses	Survey statement/ AVE score	Student responses
I am considerably more knowledgeable about the somatosensory cortex now than I was before this case. AVE=4.1		I understand how to interpret data from a two-point discrimination test. AVE=4.1	
I am considerably more knowledgeable about the homunculus now than I was before this case. AVE=4.2		Performing the two-point discrimination test helped me make connections between this material and daily life. AVE=4.1	
I am considerably more knowledgeable about phantom limb pain now than I was before this case. AVE=4.0		I would have preferred a lecture about the somatosensory cortex rather than watching a video about phantom limb pain and doing a two-point discrimination test. AVE=2.4	

Table 2. Post-case student survey.

temperature, occupation, or injury) may impact the two-point discrimination threshold. For example, students tested whether the pointer finger on the dominant hand has a lower two-point discrimination threshold than the pointer finger on the non-dominant hand. Students have also tested whether a two-point discrimination threshold was increased by probes that were warmed compared to probes that were at room temperature. Students can design and perform experimentation using the already familiar two-point discrimination test to investigate if a variable of their choosing may impact the two-point discrimination threshold. Students will apply terms such as null-hypothesis, experimental and control groups while designing their experiment. Groups can report their findings to the class as a PowerPoint presentation or, if time is limited, as a summary graph to the class.

Statistical Analysis

After gathering two-point discrimination data from all class participants, students can learn to calculate standard deviation of class data sets and to plot standard error bars on bar graphs. Students can also perform statistical analysis to test if one data set is statistically different from another and understand the importance of such a test.

Finding and Interpreting Primary Science Articles

Students can use search engines, such as PubMed, to select primary science articles that address additional methods of treatment for phantom limb pain. They can choose one figure to analyze and share with the class, similar to part two in this case. In addition, students could be asked to summarize the entire article and compare it to the article previously discussed in class. Students could be asked to describe future experimentation that builds upon the article they selected.

Investigation of Homunculus in Motor Cortex

Students can be asked to compare the homunculus in the somatosensory cortex with the motor cortex. The topics of fine motor control and gross motor control can be introduced and connected to the various sizes of body regions within the homunculus within the motor cortex.

Additional Quiz Questions with Enhanced Rigor

To enhance the rigor of quiz questions, instructors could employ more challenging, open response style questions.

For example, instead of asking, "Which body region has the highest density of receptors in the skin? A. Back of the hand, B. Back of the neck, C. fingertip", an instructor could provide a graph of two-point discrimination thresholds of the lips, thigh, calf, and dorsal surface of the foot (regions not yet discussed in this lesson) and ask students, "Using the graph provided, which one of these body regions would you predict to have the highest density of receptors in the skin? Justify your answer." Another question could be, "Which of these body regions would you predict to occupy the smallest area on the somatosensory homunculus? Explain your answer." These questions would challenge students to apply their understanding of two-point discrimination threshold and somatosensory cortical mapping to infer conclusions from novel data. Conversely, an instructor could rank body regions in order of receptor density and ask students to infer which region would have the highest two-point discrimination threshold and explain why. In addition, an instructor could draw an image of a somatosensory cortical map from a fictitious animal and ask students to use this map to identify a body region on the imaginary animal that would have the largest two-point discrimination threshold and justify their answer. Thirdly, students could be given fictitious two-point discrimination data from an imaginary animal and be challenged to properly generate a graph. Students would use the graph and their understanding about the two-point discrimination test to draw conclusions about which body region is most touch sensitive and which body region occupies the smallest area on the somatosensory cortical map.

CONCLUSION

Overall, this case provides opportunities for connectivity between course concepts and "real life" via exploration of phantom limb pain, methods to treat this pain, interpretation of the primary literature, and hands-on activities (two-point discrimination test). Furthermore, the four parts of this case are interconnected and repetitiously interleave concepts, such as the homunculus, throughout the case. Lastly, this case is flexible, and its parts can be selectively executed in a face-to-face, online, or hybrid method learning.

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APPENDIX

Phantom limb pain: feeling sensation from a limb that is no longer present and what it can reveal about our brain anatomy.

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Student handout

How is this lesson relevant to "real life"? Is it possible to feel pain from a limb that is no longer present? Yes! Some amputees report feeling pain or other sensations from an amputated or "phantom" limb. If an amputee feels pain from a phantom limb, this is referred to as phantom limb pain. If an amputee feels sensations other than pain, this is referred to as phantom limb syndrome. What is the basis for these conditions? How can one treat phantom limb pain if the limb is not present? We will investigate these questions here.

Goals:
This case will investigate phantom limb pain/syndrome and explore changes in the brain, with a special focus on the homunculus, that can happen after amputation (Part 1). We will investigate a method used to treat phantom limb pain, the mirror box, by examining the primary literature (Part 2). Lastly, this case will challenge you to perform a two-point discrimination test (Part 3) and draw connections between their two-point discrimination data and the somatosensory homunculus (Part 4).

Part 1:
In this part of the case, we will explore phantom limb pain/syndrome and a tool called "the mirror box" that can be used to treat phantom limb pain. This will be accomplished by watching a video about two amputees, Derek and James, who suffer from phantom limb pain.

Directions:
Watch the first 16 minutes of the movie, "Secrets of the Mind" and follow Dr. Ramachandran as he interviews Derek and James. While watching the video, answer the questions below. You are encouraged to pause the video at any time to answer questions. Suggested video pause points are provided in italics below.

Use these questions/answers as a study guide for a quiz during our next class.

"Secrets of the Mind" is a movie produced by PBS and NOVA. This movie can be found here:
https://www.youtube.com/watch?v=w6AfzCNDmbY

Answer the following questions in 2-3 complete sentences.
Answers to questions 1-3 can be found in the video between 3:22-10:20 minutes.

1. In your own words, describe phantom limb pain/syndrome.

2. What did Derek report feeling when Dr. Ramachandran stroked his left cheek?

3. What did Dr. Ramachandran suggest as an explanation for Derek's phantom limb pain/syndrome?

Answers to questions 4-5 can be found in the video between 10:20-13:03 minutes.

4. Describe the results from Derek's brain scan by answering these questions:
    a. What did the red color represent on the brain images?
    b. How did the red area differ between Derek's left and right hemisphere (side) in his brain?

5. Does the MRI data support Dr. Ramachandran's hypothesis? Why or why not?

Answers to questions 6-7 can be found in the video between 13:05-15:38 minutes.

6. According to Dr. Ramachandran, how does the mirror box provide relief to James?
7. Explain a mirror box by answering the following questions:
    a. What does it look like?
    b. How does one use a mirror box?
    c. Does the mirror box provide relief for James?

8. In your own words, describe the term, “somatosensory homunculus.” You are encouraged to use this link: https://www.khanacademy.org/science/health-and-medicine/nervous-system-and-sensory-infor/somatosensation-topic/v/somatosensory-homunculus

9. Referring to the video above, hand-draw a somatosensory homunculus here.

10. In what way do you think James’ homunculus, or somatosensory cortical map, might have changed after amputation?

Part 2:
In the second part of the case, you will further investigate the mirror box through the use of the primary literature.

Working with a partner, answer the following questions about a figure from a primary science article.

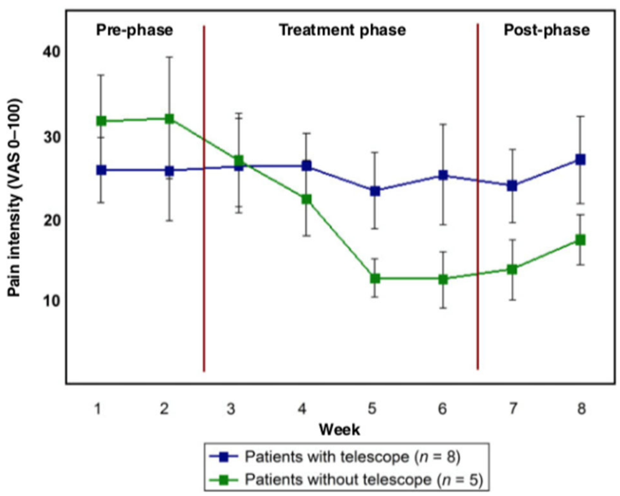

Figure 4 Difference in pain development of patients with and without telescopic distortion of the phantom limb. Error bars indicate standard error.

What is plotted on the x axis?

What is plotted on the y axis?

What do you think "treatment phase" refers to?

What does the blue line represent? And what does the green line represent?

What can you infer from the blue line? What can you infer from the green line?

Which data set appeared to respond best to the mirror box treatment? (green or blue) Explain your answer.

What are "error bars"? What information do they provide? You can research this term.

What conclusions can you draw from this graph?

What is not yet clear about this graph? List at least three questions you have about this figure.

Your instructor will now provide the abstract for this primary science article.

Read the abstract and identify three facts that provide you with a better understanding of this article. Do any of these facts help answer the questions you listed above? Explain.

What questions remain unanswered about this article? List at least two questions here:

The instructor will now provide the entire article. While you read the article, search for answers to the questions you listed above. List the answers to your questions here, or if your answers are not addressed, then explain two novel concepts that you learned from the full article.

Imagine you were an author of this study. What experiment would you do next and why?

Part 3:
In this part of the case, you will learn the biological basis of a two-point discrimination test and perform a test on a partner.

Background: the biology behind a two-point discrimination test:
The density of touch receptors in the skin varies with the body region, and these areas correspond to body areas mapped onto the somatosensory cortex on your brain. The body map is referred to as a homunculus. The density corresponds to the level of sensitivity and is measured by the "2-point threshold" or “two-point discrimination test”.

How is a two-point discrimination test administered?
Two-points of an adjustable caliper are simultaneously placed on the subject's skin with equal pressure, and the subject is asked if 2 separate contacts are felt. If so, the caliper points are brought closer together and the test is repeated until only 1 contact point is felt. The smallest distance at which the volunteer can feel 2 contacts is the “2-point threshold”. You will be measuring the two-point threshold in three body regions. If calipers are not available, you can use a wire paperclip and a ruler, or a compass.
Watch these videos to learn how to perform this test:
https://www.youtube.com/watch?v=6C8FPfHGEQg
https://www.youtube.com/watch?v=_I7KbtRwvBk

Directions to complete two-point discrimination test
1. Work in pairs. Determine who will be the subject, who will be the tester, and who will record/report data.
2. Have the subject close their eyes and ask subject to report if they feel one or two-points placed on the back of their hand.
3. Beginning with the calipers ~3 cm apart, the tester applies the calipers firmly and quickly to the back of the subject’s hand.
4. The subject reports if he/she feels one or two-points.
5. The tester continues to apply the calipers with decreasing size between the two caliper points until he/she can determine the minimum distance (measured in millimeters) at which 2 separate contacts could be felt by the subject.
6. The tester should randomly alternate applying two-points and one point to keep the subject honest in their reporting.
7. The smallest distance that a subject can correctly discern two-points is the minimum two-point discrimination distance. Record this data. (NOTE: It is important that the volunteers' eyes are closed AND that they do not know when they are going to be touched!)

Perform the "2-point threshold" test for: 1) pointer fingertip on right hand, 2) back of right hand, and 3) back of neck.
For one subject, record the minimum two-point discrimination distance in mm for each region here:

Right pointer fingertip: ____________mm
Back of right hand:________________mm
Back of neck: ___________________mm

Record this data in our classroom google excel file.

Part 4:

As a class, we will analyze our two-point discrimination data. Subsequently, we will draw connections between the two-point discrimination test (Part 3) and the homunculus (Part 1).

1. Referring to our google classroom excel file, calculate the class average two-point discrimination distance for each region and record those values here:

Right pointer fingertip: ____________mm
Back of right hand:________________mm
Back of neck: ___________________mm

2. Construct a bar graph that shows the average two-point discrimination distance for these three body parts. Be certain to label the axes appropriately.

3. Referring to the class average data, which body region has the smallest two-point discrimination distance?_______________________

4. Which of the three body regions did you find to be the most sensitive to touch? ________________

5. Referring to the "background" section in part 2, do you predict the body region with a small two-point discrimination distance would have a *low* or *high* density of receptors in the skin? Explain your answer here.

6. Based on your answer above, speculate which of the three body regions tested has the *highest* density of receptors in the skin.

7. Refer to the homunculus (Part 1) and note which of the three body regions tested (Parts 3 & 4) has the largest representation on the somatosensory homunculus. List the body region here: _______________

8. Does the body region listed in the question above have a small or large two-point discrimination distance compared to other body regions tested? ___________________

9. Let's pull it all together! What relationships do you notice between: 1) the body regions with large representations within the somatosensory homunculus, and 2) body regions with small two-point discrimination distance and 3) body regions with high density of receptors? Use your skills of observation and speculation to fill in the blanks in the sentence below.

Areas of the body with a lower density of receptors in the skin would have : 1) relatively ___________(larger or smaller) two-point discrimination distances and 2) __________ (larger or smaller) representation in the somatosensory homunculus.