The Evolution of Color Vision in Monkeys: From Nucleotides to Ecology

by
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Introduction (~30 minutes)

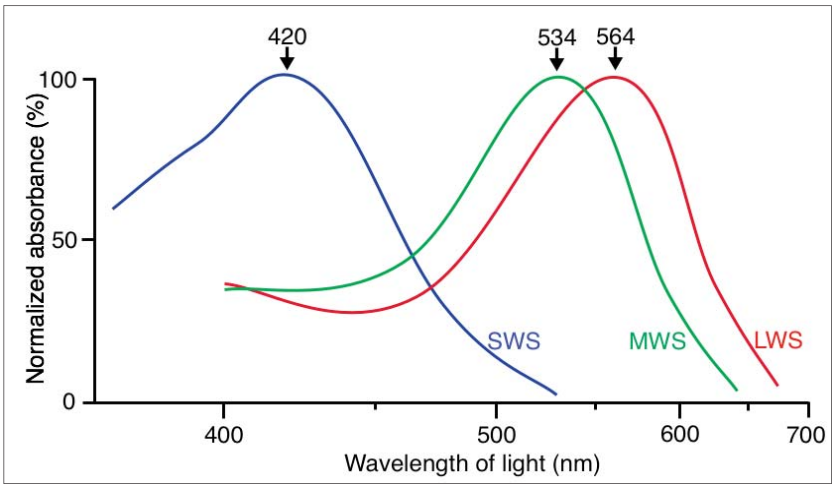
Examine the two pictures shown in Figure 1. The one on the left shows how leaves are seen by monkeys with two kinds of color receptors. The image on the right shows how leaves are seen by monkeys that have three kinds of color receptors. Monkeys with two color receptors are called dichromats while those with three kinds of color receptors are called trichromats. Incidentally, human are trichromats.

Figure 1. Leaves as seen by dichromats (left) and trichromats (right).

Look how the variety of leaf colors stands out in the full color picture (trichromatic). It offers much more detail than does the one on the left. Isn't it curious that some monkey species only have two kinds of color receptors when it seems to result in a very significant perception disadvantage?

A color receptor is a special sub-cellular structure that absorbs light. Figure 2 shows how the three different kinds of color receptors in trichromats absorb different wavelengths of light. The red, blue, and green lines are the responses of each of the three kinds of receptor. Dichromats only have two kinds of color receptors, represented by the blue and green lines.

Figure 2. Leaves as seen by dichromats (left) and trichromats (right).



We can see an amazing array of colors with just three kinds of receptors. Did you notice that the lines for the red and green just about overlap and kind of look the same? Why do you think that is? How did this happen?

A key idea in biology is that the survival of an organism and the evolution of groups of organisms depend on what happens in cells. In order to understand evolution of color vision in primates, you will need to investigate the phenomenon of color vision as it relates to different sub-disciplines of biology.

Instructions

1. Make a list of everything you know about the biology of color vision. Some items on your list may be derived from the information above while other information may come from prior knowledge about color vision that you may have. We will discuss your lists as a class.
2. After the class discussion, based on your lists and also the handout of "expert facts" about color vision that your instructor will provide you, generate a list of questions articulating any gaps remaining in your understanding of how color vision works in monkeys.
3. Propose answers to these questions (generate hypotheses).

Module: The Ecology of Color Vision (~40 minutes)

Let's continue our investigations by looking at monkeys. Where do they live? How do they find food? What does color and color vision have to do with any of that?

Instructions

Sort through your findings from the case study introduction and identify information that applies to the ecology of color vision. This information (facts, questions, or hypotheses) will be the basis for your small group investigations. You may have further hypotheses about the ecological importance of color vision, which you will have an opportunity to investigate in this module of the case study.

Investigation Phase

1. Download the Monkey Opsins Evolution Powerpoint® presentation from:
   http://evo-ed.com/PowerPoint Teaching Resources/Monkey Opsin Evolution.pptx
   These slides will be used in this module and throughout the case study.

   Slide Notes:

   - Slides 8–14 give a general background on color vision in primates.
   - Slides 15–47 cover the ecology of color vision in primates. These slides detail the importance of color for trichromatic monkeys, and pattern or shape for dichromatic monkeys in obtaining food. The central question is whether food selection is the driver of trichromacy (slide 21).
   - Slide 30 provides a link to an online foraging game that will help you to learn about foraging in dichromatic and trichromatic monkeys; slide 33 provides a link to an online color vision game.
   - Slide 47 summarizes the differences between trichromatic and dichromatic vision in monkeys with respect to food selection.

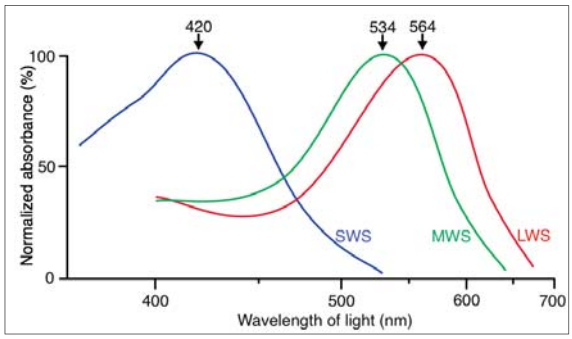
2. After viewing these slides, complete the questions below. The instructor will debrief and summarize the research with the entire class.

Homework Questions

1. Under what circumstances do dichromatic monkeys find more Kix than do trichromatic monkeys?
2. What kind of vision is associated with distinguishing food from non-food by shape or pattern? Explain your answer.
3. What kind of vision is associated with distinguishing food from non-food by color? Explain your answer.
4. Review slides 26–29 which describe an experiment on how monkeys found food. What was the overall design of the experiment to determine the importance of pattern/shape in selecting food? What did the results indicate?
5. *Evolution question:* If being a trichromatic monkey provides richer color cues than being a dichromatic monkey, why are there any dichromats at all?

Module: The Cell Biology of Color Vision (~40 minutes)

In this module, you will investigate the details of the diagram, called an absorption spectrum, which was presented in the introduction and is reproduced here (right). We also talked about three different receptors that correspond to each of the lines. These receptors are located in light sensitive cells called cones. What do we know about sensory receptors? Light receptors? What's the cell biology and the nature of receptors for color vision?



Instructions

Sort through your findings from the case study and identify the information from the introduction that applies to the cell biology of color vision. This information (facts, questions, or hypotheses) will be the basis for your small group investigations. You may have further hypotheses about the cell biology of color vision, which you will have an opportunity to investigate in this module of the case study.

Investigation Phase

1. Download the Monkey Opsins Evolution Powerpoint® slides slide set from:
   http://evo-ed.com/PowerPoint Teaching Resources/Monkey Opsin Evolution.pptx
   These slides will be used in this module and throughout the case study.

   Slide Notes:

   - Slides 48–50 give a short introduction on the cell biology of color vision.
   - Slides 52–57 outline basic cone cell function, including an embedded animation showing a simple "light to brain" pathway.
   - Slides 58–63 show the three opsin proteins and their responses to light.
2. After viewing these slides, complete the questions below. The instructor will debrief and summarize the research with the entire class.

Homework Questions

1. What is the basic pathway for color perception from light to brain?
2. What are cone cells and what is their function in the pathway described for question 1?
3. What is the one entity that varies among the three different kinds of cone cells? What is the nature of this variation?
4. What is the difference between medium wavelength (MWS) sensitive and long wavelength (LWS) sensitive receptors/opsins?
5. Why does having three color receptors (a.k.a. opsins) lead to a more complex color perception than just two?
6. What is the relationship between the chromophore (retinal) and the opsin protein of a cone cell?
7. *Evolution question:* Primates with only two types of opsin protein typically have better low-light vision than those with three opsin proteins. This is because dichromat primates typically have more rod cells than dichromat primates. What are rod cells, how do they work, and under what circumstances could having a high proportion of rod cells be evolutionarily adaptive?

Module: The Genetics of Color Vision (~40 minutes)

The genetic basis of color vision in monkeys is important to understand because there are strong connections among genes, proteins, cell biology, and how an organism functions in an environment.

In this module, you will investigate the genetics of color vision in monkeys: If there are differences in the cone cells and their respective receptor proteins, then, of course, there are differences in the genes that code for those proteins. You will also learn why color vision is considered a "sex-linked" trait in monkeys.

Instructions

Sort through your findings from the case study introduction and identify information that applies to biological central dogma (genes → proteins) and the genetic basis of color vision. This information (facts, questions, or hypotheses) will be the basis for your small group investigations. You may have further hypotheses about the genetics of color vision, which you will have an opportunity to investigate in this module of the case study.

Investigation Phase

1. Download the Monkey Opsins Evolution Powerpoint® slides slide set from:
   http://evo-ed.com/PowerPoint Teaching Resources/Monkey Opsin Evolution.pptx
   These slides will be used in this module and throughout the case study.

   Slide Notes:

   - Slides 64–72 describe the origin of the long wavelength sensitive (LWS) opsin gene. They also include information about the opsin gene location, gene duplication and gene mutation, as well as background information linking meiosis to gene duplication.
   - Slides 73–90 describe the nucleotide and amino acid differences between the medium wavelength sensitive (MWS) gene/protein and the long wavelength sensitive (LWS) gene/protein. Spectral tuning is also described.
   - Slides 91 is a recap slide of gene duplication and gene mutation.

2. After viewing these slides, complete the two sets of questions below. The instructor will debrief and summarize the research with the entire class.

Homework Questions

Set 1: Gene Duplication and Mutation

1. How many genes are responsible for trichromatic color vision? What are the genes and proteins involved called?
2. Are all opsin genes located on the same chromosome pair? Explain your answer.
3. How did gene duplication and mutation produce the information for a third type of opsin protein?
4. Explain gene duplication in the X chromosome in terms of meiotic events in an XX (female) individual.

Set 2: Nucleotide and Amino Acid Differences in Opsins

1. How many nucleotides and amino acids do the MWS and LWS genes/proteins have? Why are they so similar?
2. What are the key differences between the MWS and LWS genes and proteins? How did these differences arise?
3. What is meant by the term "spectral shift"?
4. How do these shifts provide an additional opsin protein for perceiving color?
5. Why do MWS and LWS absorption spectra look so similar?
6. List in bullet form the process of the formation of LWS receptors starting with meiosis.
7. *Evolution question:* Variation in populations is an important component of evolution. Explain how each gene duplication and mutation in general can lead to variation in a population for a given characteristic.

Module: The Phylogenetics of Color Vision (~40 minutes)

Let's look at a map of the world and look at the two continents that have lots of monkeys: Africa (Old World) and South America (New World).

Notice how the continents fit together. At one point, in the distant past, the New World and the Old World were connected as part of one contiguous land mass. What does this have to do with dichromatic monkeys and trichromatic monkeys?

Instructions

Sort through your findings from the case study and identify the information from the case introduction related to biogeography and primate evolutionary ancestry. This information (facts, questions, or hypotheses) will be the basis for your small group investigations. You may have further hypotheses about the phylogenetics of color vision, which you will have an opportunity to investigate in this module of the case study.

Investigation Phase

1. Download the Monkey Opsins Evolution Powerpoint® slides slide set from:
   http://evo-ed.com/PowerPoint Teaching Resources/Monkey Opsin Evolution.pptx
   These slides will be used in this module and throughout the case study.

   Slide Notes:

   - Slides 95–103 examine the biogeography and phylogenetics of Old/New World monkeys that account for the separation of di-, trichromatic vision in these groups.

2. After viewing these slides, complete the questions below. The instructor will debrief and summarize the research with the entire class.

Homework Questions

1. Was the common ancestor to Old World and New World monkeys likely a di- or trichromat? Explain your answer.
2. When did the split between the two groups occur? What is a reasonable hypothesis for when the gene duplication happened such that a new color receptor could evolve?
3. Explain the presence of a species of trichromatic monkeys in the New World (i.e., the Howler Monkey).
4. *Evolution question:* How could two populations of one species lead to two different species?