The Evolution of Human Skin Color

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Part I – Skin Cancer

"Stop it!" called Tatiana, playfully.

Her boyfriend, Zach, was inspecting her skin very carefully.

"Look," he answered her, his voice taking on a more serious tone. "Today a woman walked into the clinic for her annual physical. Everything about her seemed fine. She leads a balanced lifestyle, she eats well, she exercises: she's healthy! But as she was about to leave, I noticed a mole on her arm. It had many of the warning signs of skin cancer. So, I removed the mole. This woman now has to wait for the lab results to see if it was cancerous. If it is, maybe we caught it early enough to treat it, and maybe not. Either way, her life is changed. I just want to make sure you don't have any suspicious moles, okay?"

Tatiana relented and allowed Zach to examine her skin. She asked: "Do only white people get skin cancer?"

"No, people of all skin tone can get skin cancer, but it does occur more frequently in Caucasians."

Questions

1. What are the causes of skin cancer?
2. Why are Caucasians more at risk of skin cancer than other populations?
3. At what age does skin cancer *typically* occur? Is the incidence of skin cancer greater in youth or old age?

Part II – Skin Pigmentation and UV Light

Why are human populations differently pigmented? What caused the evolution of an array of different skin colors?

Humans Were Initially Lightly Pigmented

About seven million years ago, humans and chimpanzees shared a common ancestor. Since that time, the two species have evolved independently from one another. It is generally assumed that chimpanzees changed less over that time period than humans—because they have remained in their original environment. Chimpanzees are therefore often used as a surrogate to make inferences about the physical and behavioral attributes of our common ancestors.

The skin of chimps is light and covered with hair. From this observation, it has been inferred that our earliest ancestor was also probably light-skinned and covered with hair. Since humans and chimps diverged, humans left the protection of trees and adapted to a new environment (the open savannah). This change in habitat required several adaptations. Life on the savannah provided little shade and so little protection from the sun, and required a more active lifestyle (i.e., hunting as opposed to picking fruits). It is also hypothesized that the social interactions and strategizing required for successful hunting favored the development of a large brain, which consumed a lot of energy and generated heat. An increased number of sweat glands and loss of body hair evolved to dissipate heat. This created a new problem, as the light skin became exposed and vulnerable to the sun's damaging ultraviolet (UV) radiation.

Melanin: Natural Sunscreen

UV light is harmful to living organisms because it causes changes (i.e., mutations) in the DNA sequence. Skin cells that produced a pigment called melanin were advantaged because melanin is a natural sunscreen; it absorbs the energy of UV light and shields cells from the radiation's harmful effects. Such cells were favored in evolution and now all human skin cells can produce this pigment.

People vary in their skin tone due to differences in the distribution, quantity, size, and type of melanin found in their skin cells. As you might suspect, people with dark skin tend to have larger and more numerous melanin-containing particles in their skin. This provides protection from the sun's UV rays. Many genes are known to affect the production of melanin and cause skin color variation in humans. While skin color is an inherited characteristic, the fact that many genes code for this trait explains why children do not always exactly match their parents' skin tone. Tanning is the process of producing more melanin in the skin in response to ultraviolet exposure, and does not require a change in the genetic code (if a parent gets a tan, the offspring will not be more pigmented).

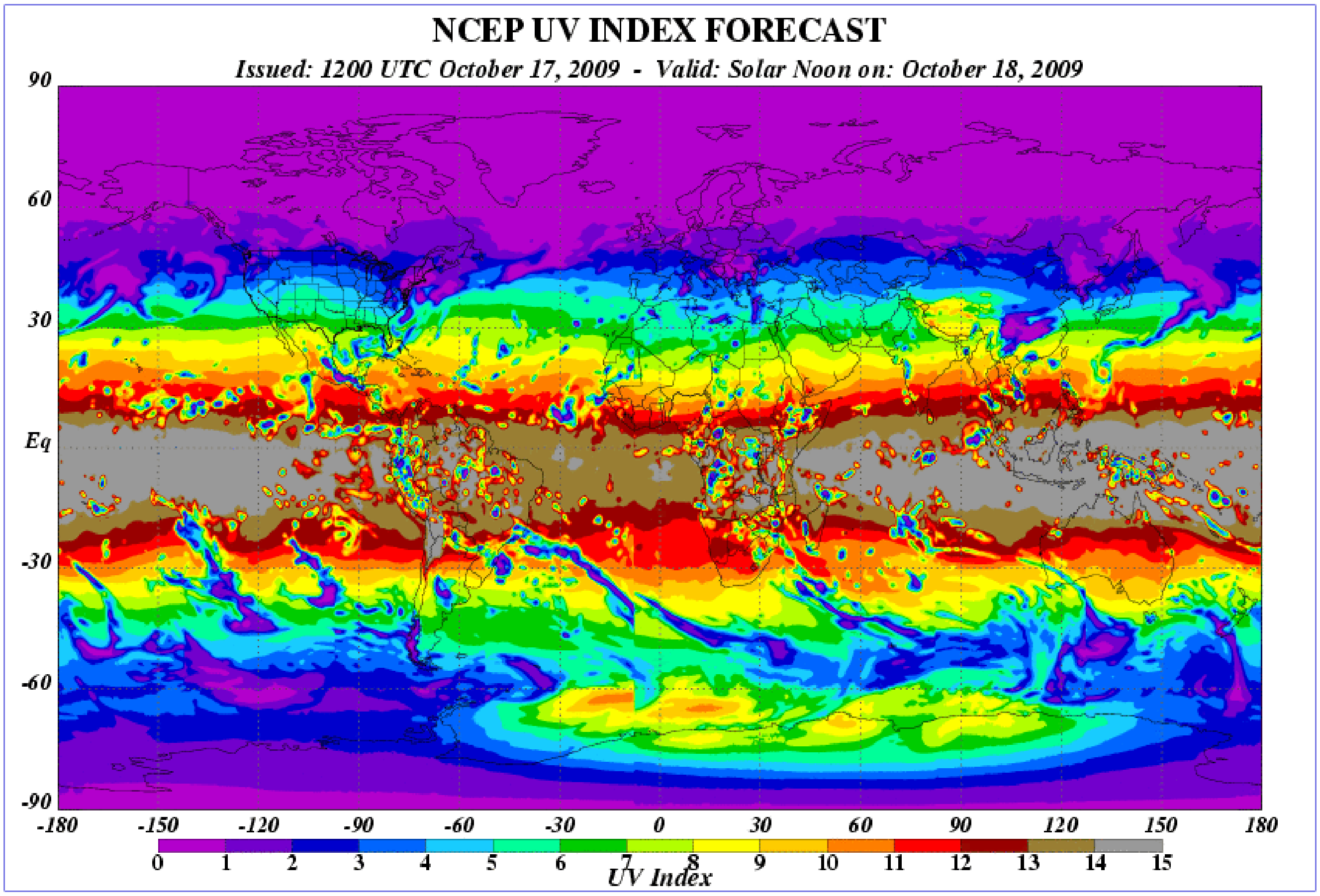
Distribution of UV Light across the Globe

The following image (Figure 1) represents a map of the world on which the UV-light Index has been superimposed. The latitudes are shown on the left (latitude helps define a location on Earth, specifically how far north or south of the equator a site is).

Questions

4. Does the amount of UV light reaching the Earth vary in a predictable manner? If so, describe the pattern you observe.
5. What latitude receives the greatest amount of UV light? The least?
6. Based on these data, where might you expect to find the most lightly pigmented and most darkly pigmented people on the planet? Be as specific as you can.
7. Provide a rationale to your answer above (i.e., why did you think that more darkly pigmented people would be found in those areas)?

Figure 1. Global UV Index Forecast.

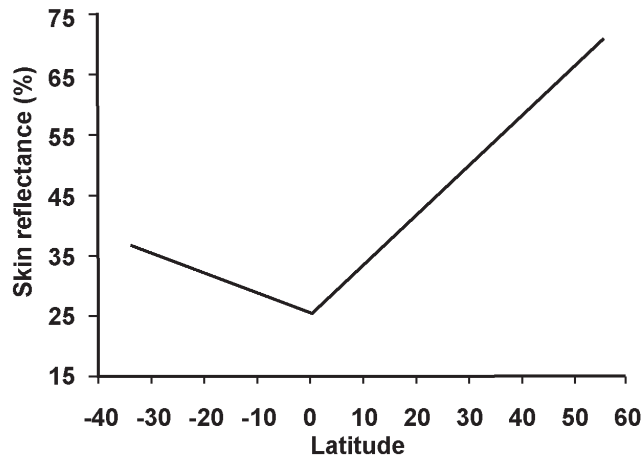


Source: Figure obtained from the National Oceanic and Atmospheric Administration. Graph retrieved 18 October 2009 from http://www.cpc.ncep.noaa.gov/products/stratosphere/uv_index/gif_files/uvi_world_f1.gif. This U.S. Government material is not subject to copyright protection within the United States.

Part III – Distribution of Skin Tones across the Globe

Let's examine whether our predictions were correct. Figure 2 shows the relationship between latitude and the average skin reflectance of populations located throughout the world. Skin reflectance is a measure of pigmentation. The more a skin reflects light, the lighter it is in tone.

Figure 2. Relationship of skin reflectance to latitude.



Source: Panel B of Figure 2 in Barsh (2003). Graph originally captioned as "Summary of 102 skin reflectance samples for males as a function of latitude, redrawn from Relethford (1997)."

Questions

8. Interpret this graph and the trend it describes.
   a. Is skin reflectance randomly distributed throughout the globe? If not, how would you describe the pattern?
   b. Restate your findings in terms of skin color and UV light (instead of skin reflectance and latitude).
   c. How closely do these findings match the predictions of your hypothesis (Question 6)?
   d. Some populations have skin colors that are darker or lighter than predicted based on their location (their data point falls somewhere outside of the line shown in Figure 2). What might explain the skin color of these exceptional populations? Propose a few hypotheses.
9. Hypothesize why different skin colors have evolved. Based on what you know, what factor is most likely to exert a selective pressure on skin color?

Part IV – Natural Selection and Evolution of Skin Color

Based on the information provided so far, it seems reasonable to hypothesize that darker skin evolved to protect against the harmful effects of UV light. In particular, individuals who lacked optimal pigmentation for tropical latitudes had a greater risk of skin cancer and death.

Until fairly recently, this was the leading hypothesis about the evolution of skin color. However, there is a problem with this hypothesis. Let's see if you can find it.

Here is some basic information on evolution by natural selection. Evolution is a change in the gene pool of a population of organisms from generation to generation. Natural selection is but one of several mechanisms by which evolution can take place. Through natural selection, populations evolve and become adapted to their specific environment. Natural selection will occur if the following three conditions are present:

- *Variation:* The organisms in the population vary with regard to a trait.
- *Heredity:* Variation in the trait has a genetic component transmissible to offspring.
- *Selective Pressure & Differential Reproductive Success:* Some traits increase the odds of surviving to reproductive age and successfully producing and rearing offspring in a given environment. Such traits are more adaptive. Those organisms having the better adapted trait leave more offspring behind—they are "naturally selected." In the next generation, this adaptive (and inherited) trait will increase in frequency and will be represented in a greater proportion of the population. At this point, the genetic makeup of the population is different from that of the starting population: the population has evolved.

Evolution is really a "number's game": the organisms that reproduce the most "win" because their traits will be disproportionally represented in the next generation.

Note also that individuals do not evolve. They either breed more effectively or less effectively, depending on already existing differences in their traits. Only populations evolve or change over time.

Questions

10. Review your answer to Question 3. Keeping your answer in mind, how strong a selective pressure do you expect skin cancer (UV-induced mutations) to exert on reproductive success?
11. Based on this information, does your hypothesis about the evolution of skin color (Question 9) seem likely? Why or why not? How does skin color meet, or fail to meet, the three requirements of natural selection outlined above?

Part V – Folate: A Different Way of Looking at It

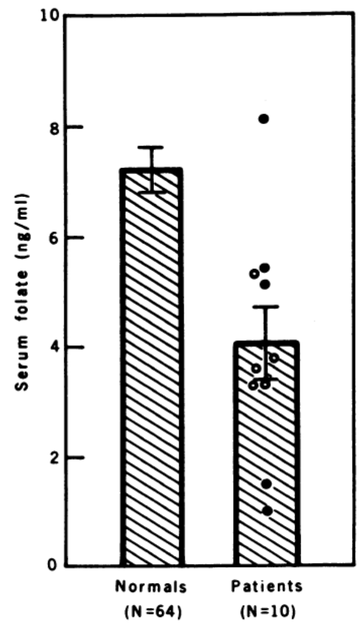
Since skin cancer tends to occur after age 50, it has little impact on reproductive success. Consequently, skin cancer probably exerted little pressure on the evolution of skin color. Some other factor must explain the range in pigmentation that is observed in the human population.

For years, this fact was overlooked by the scientific community, and the consensus was that dark skin had evolved as protection against skin cancer. In 1991, the anthropologist Nina Jablonski was skimming through scientific journals when she came upon a 1978 paper by Branda and Eaton.

This paper investigated the effects of sunlight on an essential chemical found in our body: folate or folic acid (one of the B vitamins). Folate is an essential nutrient for DNA synthesis. Since cells reproduce at a fast pace during fetal development (and hence, there is a lot of DNA replication), the highest levels of folate are needed during pregnancy. Folate deficiencies during pregnancy can lead to anemia in the mother and malformations of the nervous system (neural tube defects in particular), gastrointestinal system, aorta, kidney, and skeletal system in the fetus. There is also a high rate of miscarriages. In addition, folate deficiency has been linked to spermatogenesis defects (inability to form sperm) in mice and rats (Mathur et al., 1977), and anti-folate agents are being investigated as a form of male contraceptive (Cosentino et al., 1990).

Branda & Eaton's paper measured the folate concentration in two human test groups. The results are shown in Figure 3. One group (called "patients") was exposed to UV-light, while "normals" were not so exposed.

Figure 3. Levels of blood folate in people exposed and not exposed to UV light.



Patients were exposed to UV light for at least 9 hours every day for 3 months. The difference between the two groups was statistically significant ($P < 0.005$). Brackets represent the standard error of the mean.

Source: Figure 1 from Branda, R.F., and Eaton, J.W.(1978). Skin color and nutrient photolysis: An evolutionary hypothesis. *Science* 201: 625–626. Reprinted with permission from AAAS. This figure and Table 1 may be used for non-commercial and classroom purposes only. Any other uses require the prior written permission from AAAS.

Question

12. Based on Branda and Eaton's results (Figure 3), what is the apparent effect of UV light exposure on blood folate levels?

Folate was isolated from blood and placed in a test tube. Half of the test tubes were exposed to UV light for 1 hour. The folate concentration in the samples was measured. The results are indicated in Table 1.

Table 1. Folate concentrations in four samples of human plasma before and after a 1 hr exposure to UV light *in vitro.*

Time	Folate (ng/ml) in sample				
	1	2	3	4	Mean
	Radioassay				
Before exposure	6.0	6.7	3.2	6.1	5.5*
After exposure	3.6	4.6	1.5	4.3	3.5*

Source: Table 1 from Branda, R.F., and Eaton, J.W.(1978). Skin color and nutrient photolysis: An evolutionary hypothesis. *Science* 201: 625–626. Reprinted with permission from AAAS.

Question

13. What is the apparent effect of UV light on folate levels in these test tubes?

Folate levels in humans are determined by two things: (1) dietary intake and (2) destruction through alcohol consumption or ultraviolet skin exposure.

Questions

14. How is folate linked to natural selection?
15. All other things being equal, which skin tone would you expect to be correlated with higher levels of folate?
16. Based on this new information, revise your hypothesis to explain the evolution of human skin color.
17. What would happen to the reproductive success of:
    a. A light-skinned person living in the tropics?
    b. A light-skinned person living in the polar region?
    c. A dark-skinned person living in the tropics?
    d. A dark-skinned person living in the polar region?
18. Predict the skin tones expected at different latitudes, taking folate needs into consideration. Use the world map (Figure 4) to indicate the skin tone expected at each latitude (shade the areas where populations are darkly pigmented).

Figure 4. Map of the world.

Source: http://commons.wikimedia.org/wiki/File:World_map_blank_black_lines_4500px_monochrome.png, CC BY-SA 3.0.

19. Can folate explain the variation and distribution of light- and dark-skinned individuals around the world?

Part VI – Vitamin D: Still Another Way of Looking at It

Folate can explain why dark skin evolved, but it cannot account for the evolution of light skin. Another factor must be at play.

Vitamin D_3 is essential for normal growth, calcium absorption, and skeletal development. It is particularly important in maintaining and repairing healthy bones and teeth. Its role in calcium absorption makes it essential in maintaining a healthy heart, blood clotting, a stable nervous system, and an effective immune system. Deficiencies manifest themselves as rickets (softening of the bones), osteoporosis, and osteomalacia. It can lead to death, immobilization, or deformities. Women have a higher need for this nutrient during pregnancy and lactation due to their need to absorb calcium to build the fetal skeleton.

Humans can obtain vitamin D_3 by one of two means. They can consume it in certain foods (fish liver oil and, to a lesser extent, egg yolk are good sources). Alternatively, skin cells have the ability to synthesize it from a cholesterol-like precursor. However, this process requires the energy of UV radiation.

Theoretical research on the dose of ultraviolet radiation required to produce vitamin D_3 suggests that for moderately to darkly pigmented individuals (Figure 5):

- There is enough sunlight reaching the tropics (approximately 5° north of the Tropic of Cancer to approximately 5° south of the Tropic of Capricorn) to meet all of a human's requirement for vitamin D_3 throughout all months of the year. This is indicated by the dotted area on the map. *Note:* Vitamin D_3 is not produced to toxic levels when high quantities of sunlight are present.
- In the area indicated by narrowly-spaced obliques, there is *not enough* ultraviolet light to synthesize vitamin D_3 in human skin for at least 1 month of the year;
- In the area indicated by widely-spaced obliques, there is *not enough* UV light for the skin to synthesize vitamin D_3 in any month of the year

Figure 5. Amount of UV light available to synthesize recommended levels of vitamin D for a moderately to darkly pigmented person at various locations around the world.

Source: reprinted from *The Journal of Human Evolution* 39(1), Jablonski, N.G., and G. Chaplin, The Evolution of human skin coloration, pp. 57–106, Figure 2, copyright (2000), with permission from Elsevier. http://www.sciencedirect.com/science/journal/00472484.

Questions

20. How is vitamin D linked to natural selection?
21. Which skin tone allows someone to maintain the recommended level of vitamin D?
22. Based on this new information, revise your hypothesis to explain the evolution of the variation and distribution of human skin color.
23. Taking only vitamin D into consideration, what would happen to the reproductive success of:
    a. A light-skinned person living in the tropics?
    b. A light-skinned person living in the polar region?
    c. A dark-skinned person living in the tropics?
    d. A dark-skinned person living in the polar region?
24. Predict the skin tones expected at different latitudes, *taking only* vitamin D needs into consideration. Use the world map (Figure 6) to indicate the skin tone expected at each latitude (shade a region to represent pigmented skin in that population).

Figure 6. Map of the world.

Source: http://commons.wikimedia.org/wiki/File:World_map_blank_black_lines_4500px_monochrome.png, CC BY-SA 3.0.

25. Can vitamin D alone explain the current world distribution of skin color?

Evolution by natural selection is a process of compromise in which costs are minimized and benefits are maximized. Both light and dark skins have costs and benefits. As you are probably now realizing, adopting one level of pigmentation has trade-offs.

26. Using principles of natural selection, predict the skin tone expected at different latitudes, taking *ultraviolet exposure, vitamin D, and folate* needs into consideration. Use the map (Figure 7) to indicate skin tone patterns at different latitudes (shade regions where populations are expected to be darkly pigmented).

Figure 7. Map of the world.

Source: http://commons.wikimedia.org/wiki/File:World_map_blank_black_lines_4500px_monochrome.png, CC BY-SA 3.0.

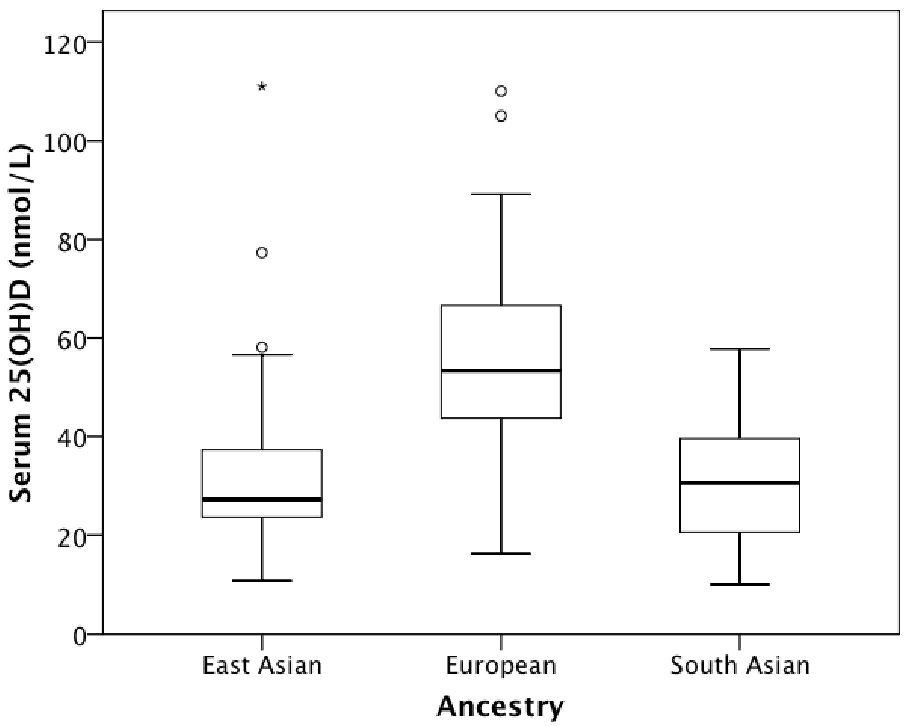
27. Are UV light, vitamin D and folate needs sufficient to explain the current world distribution of skin color?
28. How might you explain that Inuits, living at northern latitudes, are relatively dark-skinned (much more so than expected for their latitude)? Propose a hypothesis.
29. Conversely, Northern Europeans are slightly lighter-skinned than expected for their latitude. Propose a hypothesis to explain this observation.

Part VII – Adaptation in Progress

While reading the newspaper, you stumble upon an article called "Are you getting enough vitamin D" (Mittelstaedt, 2007). It describes the results of a recent study on the vitamin D blood levels of students at the University of Toronto. The results are analyzed by the students' ancestry. Intrigued by these findings, you obtain and read the original research paper (Gozdzik et al., 2008).

The figure below shows the levels of vitamin D found in the blood of Canadian students, shown by their ancestry (Gozdzik et al., 2008). The bottom of each box represents the 25th percentile of the data, the top of the box represents the 75th percentile, and the horizontal bar within the box is the median (the value below which 50% of all data points fall). 25-hydroxyvitamin D [25(OH)D] levels greater than 75 nmol/L are considered optimal (Holick & Chen, 2008). Note that similar results would be found in the United States (Calco & Whiting, 2003; Bodnar et al., 2007).

Figure 8. Amount of vitamin D in blood of Canadians, shown by ancestry.



Source: Gozdzik *et. al.* 2008.

Questions

30. Which populations have insufficient amounts of vitamin D in their blood?
31. What is a common trait to all of these populations? How could this explain their deficiency?
32. For several decades, milk and cereals have been fortified with vitamin D to help increase intake of this nutrient. Hypothesize why these fortification programs appear to be failing in some ethnic groups (there may be different reasons for different groups).
33. What should some Canadians do to avoid vitamin D deficiency?

34. If individuals do not take steps to boost their vitamin D intake, hypothesize what might happen to their descendants in the future.
35. What might happen to Australians of European descent over time?
36. Think of the forces that affected the evolution of skin color in the past. Contrast these to the factors that affect skin pigmentation today. Hypothesize about the factors that may affect skin pigmentation in the future.
    a. Do you think the impact of natural selection on skin color is as strong today as it was in the past?
    b. What factors may have decreased or increased selection today?
    c. Predict skin color distribution in the year 2500. Outline your assumptions and the reasons for your predictions.

To beat the "winter-blahs," a person of European descent is planning a trip to the Caribbean. Consider all the evidence you have learned in this case and apply it to this situation. What would you advise this lightly-pigmented person to do on the trip?

Questions

37. During the trip, the lightly-pigmented individual is looking forward to lying on a beach and working on his/her tan. Will this person be adapting to the environment (in a Darwinian sense)? In other words, will evolution take place by developing a tan in a geographical region of intense UV light?
38. Should the lightly-pigmented person wear sunscreen on the trip?
39. Should this person wear sunscreen when he/she is at northern latitudes (i.e., at home in Canada)?

Part VIII – Sexual Selection Too?

Sexual selection is a special type of natural selection. Darwin was the first to recognize that if males or females of a species choose their mate based on a particular trait, then their preference will exert selective pressure on that trait. The result is that the opposite sex will evolve to meet that preference. An obvious example is the peacock's tail. If females prefer males with the longest and most ornate and iridescent tail as mates, even if having such a tail seems detrimental to the male's survival, it may be selected for evolution. This is because reproductive success, and not survival *per se,* is the most important characteristic that drives evolution. Females might prefer males with elaborate traits because it is a real signal of health and genetic worth; only males with good genes can afford to have such a handicap (such a large and cumbersome tail). This process is called *sexual selection*. It occurs when individuals in the population differ in their ability to attract a mate.

Research by Nina Jablonski and George Chaplin suggest that women generally produce 3–4% less melanin in their skin than do men in all populations of the world.

Questions

40. How might this observation be the result of sexual selection? Explain your reasoning.
41. Could this observation be the result of "normal" natural selection (i.e., not sexual selection)? Explain your answer.

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