Congenital Deutan Defects of Color Perception in Mission Specialists

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Contents

Chapter 1

Executive Summary

This document addresses a narrow question: Should NASA relax its standard for mission specialist applicants who have congenital deutan color deficiencies? To answer this question, we examine the following 5 claims:

(1) On an absolute scale, there is little or no risk in allowing congenitally deuteranomalous or congenitally deuteranopic persons to be mission specialists;

(2) On a relative scale, the risk in allowing congenitally deuteranomalous or congenitally deuteranopic persons to be mission specialists is substantially lower than other medical risks NASA currently accepts;

(3) NASA's existing color vision standard is flawed in both design and execution;

(4) Relaxing the standard yields aeromedical benefits.

(5) Relaxing the standard yields societal benefits.

We show that all 5 of these statements are true, making a compelling case for relaxing the standard. The remainder of this Summary highlights the evidence behind each of the statements above.

{1} Absolute Risks of Relaxing the Standard

Color is but one of many channels by which the human visual system receives information. Thus, isolated color perception defects are potential risks to safety and/or mission accomplishment only when color is the sole means by which information is transmitted. Mission specialists work in 3 aero-visual environments:

(a) **Intra-vehicular:** NASA design requirements, in effect at least since 1981, mandate that all coding systems used in spacecraft must be safe for color deficient persons. This requirement applies to the forthcoming International Space Station as well.

(b) **Extra-vehicular:** NASA design requirements for spacecraft orientation lights require color discrimination capabilities well below those demanded by the current standard. It is almost impossible to posit a scenario in which spacecraft orientation lights supply non-redundant information.

(c) **Aviation:** Normal or near-normal color vision is not required for a mission specialist's aviation duties because:

  (i) Mission specialists have not been required to perform pilot duties since 1978.
  (ii) Mission specialists fly backseat in an airplane (the T-38) designed to operate as a single seat aircraft.
  (iii) It is not operationally realistic to posit a nonpilot trying, even in an emergency, to land a T-38.

  The case is strengthened further by the fact that color perception is not a limiting factor for *pilots*:

  (iv) Night vision goggles deliver a monochromatic (one-color) image to their wearer, yet they are routinely used by pilots of high performance single-seat military aircraft and in the world's most crowded airspaces.
  (v) Poor testing practices allowed scores of color defective men to become pilots for the US military, without evidence of subsequent compromised safety or effectiveness.
  (vi) The Australian court system, in a detailed, comprehensive, balanced assessment in 1989 could find no reasonable non-redundant use of color in commercial aviation. As a result, Australia today has no color vision requirement for cilivian pilots.

  It is also worth noting:

  (vii) Additional color factors encountered in military aviation, such as flash protection systems, do not apply to NASA's civilian mission.

(viii) In another color-intensive military field, the US Navy has granted color vision waivers for service aboard submarines.

{2} Relative Risks of Relaxing the Standard

Medical standards weigh risk against benefit. It is instructive, therefore, to examine various NASA standards to gauge the risk deemed acceptable for astronaut applicants.

(a) The current NASA standard for uncorrected visual acuity is 20/200. Legal blindness is defined as 20/200 vision.

(b) Sickle cell trait is acceptable for astronauts, despite the fact it can cause sudden unexpected vascular catastrophes, and even death, at altitides as low as 4000 feet.

(c) Physical strength is an asset for a space crewmember, especially in unexpected or emergency situations not anticipated by NASA human factors requirements. Yet there is no minimum strength requirement.

(d) John Glenn.

{3} Flaws in the Current Standard

The current standard for color vision, based on the Farnsworth Lantern (Falant), is both flawed in its application and inconsistent with facts concerning color perception in an operational aerospace environment:

(a) NASA knew the chief of the astronaut office in 1989 was severely color deficient. Yet, he remained on flight status, later piloting both the T-38 and at least two space shuttle missions.

(b) Studies consistently show that, on an individual basis, performance on the Falant is not tightly correlated with performance of real-world lantern tasks.

(c) Some protanopes can pass the Falant.

(d) Corrective lenses are permitted for legally blind astronauts. Colored filters are not considered for applicants who are color defective.

{4} Aeromedical Benefits of Relaxing the Standard

Color defective persons sometimes have an advantage over persons with normal color vision:

(a) Color defective persons can perceive color patterns that color normal persons cannot. This is shown by certain color vision tests, as well as the well-known fact that camouflage is less confusing to color defectives.

(b) Color defective persons are more adept at discriminating textural differences than color normal persons.

(c) Limited evidence suggests that color defective persons may operate better than color normal persons in mesopic lighting conditions and in vibrating environments.

(d) A diversity of perceptual abilities in a space crew enhances the overall information content available to the crew.

{5} Societal Benefits of Relaxing the Standard

Medical standards are formulated not in isolation, but within a framework of legal principles and societal goals.

(a) NASA has already flown a color deficient astronaut. Therefore, it may not prove legal to now deny employment as an astronaut to persons with the same or lesser degree of color deficiency.

(b) The Americans with Disabilities Act, and the Rehabilitation Act of 1973 upon which it was largely based, both require that employers make reasonable efforts to accomodate persons with physical requirements outside the norm. It cannot be argued that additional personal equipment, specifically, filter-equipped spectacles, are unreasonable accomodations for a color deficient astronaut.

(c) NASA's current color vision standard excludes the talents of 8 million American males from the astronaut corps. By comparison, sickle cell trait affects less than 3.5 million Americans.

{6} Conclusions and Recommendations

The issue is not whether color defective persons can perceive colored stimuli in various artificial situations. The issue is what difference it makes with regard to safety and mission accomplishment. The evidence presented in this document shows that congenital deuteranopia would threaten safety and mission accomplishment to a far lesser degree than the risk NASA already accepts.

Thus, we recommend that congenital deutan color deficiency, of whatever degree, should not be disqualifying for mission specialist duty. The specific recommendation is as follows. Note that, like the current standard, it ignores the possibility of tritan (so-called "blue-yellow") defects. Also, like the current standard, it assumes that complete and detailed ophthalmological and physical examinations are performed.

(1) Pseudo-isochromatic plates are administered first. Examinees earning a passing score are judged to have adequate color vision and no further testing is performed. Examinees who do not earn a passing score go to step 2.

(2) The color vision defect is categorized using a test such as the Farnsworth D-15, the Farnsworth 100 hue test, or the Nagel anomaloscope. If the defect is deutan in nature, the examinee goes to step 3. This document does not address the disposition of a protan defect.

(3) It should be determined whether the defect is congenital and isolated. In many cases, historical records will show color deficiency detected years beforehand. Gene sequencing, available in several university laboratories, definitively establishes the diagnosis of congenital color vision deficiency. Because acquired color vision defects are generally associated with ocular pathology [1(p. 33)], the existing NASA ophthalmological and physical examination, should rule out superimposed ocular and systemic disease. It may be worthwhile to add tritan color testing to screen for acquired color vision defects. If the color vision defect is congenital and isolated, the examinee proceeds to step 4.

(4) The examinee is judged to have adequate color vision. If accepted as a mission specialist candidate, the examinee should undergo training concerning the limitations of his or her color perception abilities and training in the use of associated personal equipment, if any.

Chapter 2

A Brief Introduction

2.1 General approach

This paper addresses the question of whether NASA's color vision standard should be relaxed. A complete re-examination of the standard would have to consider all combinations of the 3 factors below:

Etiology of color vision defect	congenital / acquired
Type of color vision defect	protan / deutan / tritan / mono-/achromat
Crew position	pilot / mission specialist / payload specialist

This paper considers only one of the combinations: congenital deutan deficiencies in mission specialists. For convenience, we will henceforth refer to it as the "MS deutan standard."

After a brief historical review, the remainder of this section discusses selected physiological aspects of color vision which will be necessary to understand some of the later parts of this document.

For the reader's convenience, full-text copies of the first 5 references are provided at the end of the document.

2.2 History

In the late 1800s, a few railway accidents occurred in Europe which learned men blamed on defective color perception in railway workers. Although it is now accepted that these accidents were due to other factors [82], minimum standards for color vision were adopted soon thereafter by several national railway systems, and by the maritime industry soon after that.

When mankind took to the air, airplanes were unreliable and pilots often needed to pick out an emergency landing site quickly. Color vision was a critical element in distinguishing, for example, a field of potatoes (bad landing field) from a field of newly cut hay (good landing field) [74, 84]. Color vision requirements were, therefore, adopted by the aviation community.

Today, NASA's color vision requirement is the same as those of the US Navy and Air Force: anyone who passes a set of pseudoisochromatic plates or the Farnsworth lantern (Falant) is acceptable. The Falant is the easier of the two tests. It was invented by the US Navy Submarine Medical Research Laboratory in the 1940s [31] and has been the Navy's final arbiter of color fitness for its submarine, surface, and aviation forces since 1954 [47]. The US Air Force adopted the Falant as its final arbiter in the 1980s, having previously used the VTA-CTT "color wheel" test as its gold standard.

2.3 Color vision physiology

Although 8 to 10% of ethnically European men have a congenital defect of color perception, color vision deficiency was not described as a medical entity until 1777 [63]. This fact emphasizes that people with congenital color vision deficiencies function completely normally in a pre-industrial world.

Reference [1] is an introduction to the physiology of color vision. Several of its points should be emphasized:

a) Congenital defects of color vision are, by definition, fixed and unchanging.

b) Congenital deutan defects of color vision are isolated defects of color perception, i.e., there are no additional perceptual defects nor ocular nor systemic pathology. Processing of texture, contrast, shape, motion, and light sensitivity are all normal.[1]

c) Gene sequencing is available in several university laboratories to definitively make the diagnosis of congenital color deficiency. It is not possible, however, to predict phenotype from genotype.

Terminology note: "deutan" is used to mean the union of deuteranopes and deuteranomals, while "protan" means the union of protanopes and protanomals.

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[1] Protan defects are associated with a reduced ability to perceive red light. That is, in some situations, normals and deutans will recognize that a light is present whereas a protan will not.

2.3.1 Color confusions

Each type of color defective (protan, deutan, tritan) has its own characteristic set of color confusions. These "confusion axes" can be represented schematically on what is known as the CIE plane:

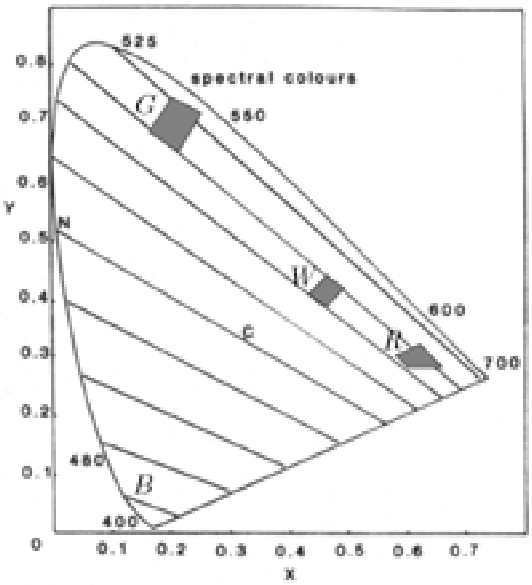

Figure 2-1. Deuteranopic color confusions. Any hue can be completely specified by X and Y coordinates on the CIE plane. The rounded triangle bounds the set of colors visible to the human eye. Spectral colors lie on the rim; their wavelengths are shown (nm). The straight lines are the color confusion lines for deuteranopes. The areas labeled R, W, and G represent the red, white, and green colors used in the Falant [62]. B = blue. The CIE plane gives no information about luminance or brightness. Adapted from [11].

A deuteranope will confuse colors that lie on, or close to, any of the lines shown in figure 2-1. A deuteranope has difficulty with the Falant because the Falant's three colors are deliberately chosen to lie on a color confusion line for deuteranopes (and for protanopes, too, although we do not show that).

A deuteranope will not confuse blue and green because they are not co-located on a color confusion line. The color confusion lines for deuteranomalous subjects will be shorter than the deuteranopic lines pictured.

We will return to color confusion loci later in the document.

2.3.2 Small fields and the Falant

It should be no surprise that the US Navy was the first to adopt a lantern test as its standard color vision test. The Falant "duplicates the visual task of a lookout" [31]. Even in 1998, "judging colored lights at sea [is] the most critical color-related task that Naval Officers perform" [48].

Interestingly, judging the color of small lights is the most difficult act for the human color vision system to perform. Color perception becomes markedly easier as the visual angle of the stimulus increases [28, 39, 58, 67], to such a degree that in one series *all* deuteranopes were able to make near-normal trichromatic distinctions on a large (31°) field [39].[2] It is thought that stimulating a larger number of cones somehow makes up for the inefficiency of the individual cones.

Thus, lantern tests are ideal from the Navy's perspective because (1) they assess the ability of the most important color task, and (2) they exercise the color vision system to its maximum.

This is fair and reasonable if the job demands the degree of color discrimination required by the lantern. The next chapter of this document shows that the degree of color proficiency required of the mission specialist is nearly nil.

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[2] Nagel, the inventor of the anomaloscope, who behaved as a deuteranope on his own instrument, reported that he was able to distinguish between the red and green navigation lights of the steamers on Swiss lakes when the observation angle of the lights was enlarged by reflection on the water's surface [39].

Chapter 3

Absolute Risks of Relaxing the Standard

3.1 NASA experience with color defective astronauts

The only hard data available suggest that the the risk of allowing color deficient astronauts to fly the space shuttle and the T-38 is zero.

In 1989 the Houston Chronicle reported that NASA's chief astronaut, Daniel C. Brandenstein, was color blind, having failed the Falant in 1987 [3]. NASA gave no official comment, but sources have confirmed to me that Brandenstein's color defect was common knowledge in the astronaut office, to the point where he was once given a large black and white picture by other astronauts, with the title "The World as Dan Sees It." The defect is apparently severe: "During an interview, Brandenstein, when asked to identify the color of his interviewer's green necktie with black stripes replied 'gray with black stripes' " [3].

Brandenstein was selected as a pilot astronaut in 1978. He flew space missions in 1983, 1985, 1990, and 1992. Thus, he was allowed to command the 1990 and 1992 space shuttle missions and to *pilot* the T-38 with NASA's full knowledge that he was color defective.

3.2 Color perception aboard NASA vehicles

3.2.1 The T-38

Backseat Duties. The T-38 is a 2-seat, high-performance aircraft flown frequently by astronauts. Mission specialists normally occupy the back seat when they are aboard. Because the T-38 can be nominally operated in a single-seat configuration, there is no requirement for a person in the backseat. This implies there is no requirement for a normal color perception system in the backseat.

Concern surrounding a color deficient backseater would only arise if the backseater were not aware of his defect, and transmitted false information to the pilot. This can only be avoided by educating the backseater about the nature and limits of his color perception. Given the overachieveing characteristics of persons selected for the astronaut program, this is assumed not to be an issue.

It might be argued that, in an emergency, the backseater may be called upon to land the aircraft. This possibility is rare, a fact which no doubt contributed to NASA's decision to drop pilot training for mission specialists in the early 1980s. If operational NASA policymakers felt it was important to have all mission specialists prepared to land the T-38 in an emergency, then the flight training requirement would not have been dropped or NASA would require that mission specialists be trained as T-38 pilots before entering the program.

Realistically, the ejection seats would be used in an emergency. The success rate of modern ejection seats must be orders of magnitude greater than the success rate of nonpilots landing a T-38 for the first time. This is especially true given what Apollo 11 astronaut Michael Collins says about landing a T-38:

> Like the F-104, it is not especially good at low speeds, and, in fact, the T-38 jiggles, shakes, and buffets its way around the landing pattern to the point where it is difficult to recognize an impending stall, since the traditional stall warning of airframe buffet cannot be used. The Navy apparently found this low-speed buffet condition unsatisfactory and has not purchased any T-38s as basic trainers, but the Air Force uses them very successfully [23].

Frontseat Duties. If one does not accept the arguments above, there are several lines of evidence suggesting that normal color vision is not a requirement for even the *frontseater*.

(a) Night vision goggles (NVGs) deliver a monochromatic image to the wearer. Thus, when a pilot wears them, he or she has no color vision at all. NVGs are used routinely in military aviation, e.g. by Navy F-18 pilots, during all phases of the mission. One might argue that military operations are often conducted in restricted airspace where traffic densities are lower. However, aircrew of the 129 Rescue Wing of the California Air National Guard wear NVGs, even though its home base of Moffett Field is located in airspace as crowded as anywhere on the planet – in the middle of a triangle defined by the busy international airports in San Francisco, Oakland, and San José.

(b) Because of lawsuits brought by deuteranopic pilots [8, 2, 7], the Australian court system has examined, in detail, the role of color vision in flying modern aircraft. After hearing testimony from academics, pilots, and flight surgeons; after viewing cockpit films fed through a deuteranopia simulator; and after visiting a Boeing 767 simulator; the court concluded in a 21-page decision that deuteranopia does not significantly degrade the ability of a pilot to fly an airplane safely [2]. As a result, deuteranopes may gain virtually unrestricted civilian pilot licenses in Australia. (The only restriction is that the airplane must have a radio.)

(c) As discussed in detail later, for many years both the Navy and Air Force accepted many color defectives who did not meet color standards for aviation or submarine duty, with no apparent compromise in safety.

Conclusion. There is no evidence to suggest that a deuteranopic mission specialist, functioning as the backseater in a T-38, imperils safety or mission accomplishment whatsoever – provided he is educated about his defect.

3.2.2 Shuttle and Space Station – Interior operations

NASA's policies on color use aboard space vehicles are contained in two publications: Mans-Systems Integration Standards, NASA-STD-3000 [5], and International Space Station Flight Crew Integration Standard, SSP 50005 [56]. These documents are almost identical; we will refer mainly to the former. This section and the next draw heavily on these documents.

The NASA documents describe three major uses of color inside spacecraft: (1) coding, (2) decor, (3) night vision preservation (red light). We are not going to address the issue of decor at all. Because we are concerned only with deutan defects, we are also not going to consider the issue of red light for darkness pre-adaptation; deutans will have the same physiology as normals. Thus, our discussion will concern only coding.

Uses of Color Coding. STD-3000 says: “Coding should be used to improve the information processing ability of crewmembers. Applications include, but are not limited to, the following:

1) Highlighting of:
    a) Critical information.
    b) Unusual values.
    c) High priority messages.
    d) Error in entry.
    e) Items requiring a response.
    f) New information.
2) Facilitation of:
    a) Discrimination between individual display elements.
    b) Identification of functionally related display elements.
    c) Indication of relationship between display elements.
    d) Identification of critical information within a display.
    e) Discrimination of controls. [5(§9.5.2.d)]”

The words “highlighting” and “facilitation” suggest non-critical functions. Indeed, NASA distinguishes between *coding* and *labeling*. Labeling provides unambiguous, definitive associations; coding, as the list above shows, is typically used to make life easier. Of note: Color is but 1 of 8 types of coding that NASA recognizes: brightness, size, pattern, location, shape, font, and flash are the others [5(§9.5.3.2)].

We reviewed reference [5] in detail to understand where and how color coding is used in intravehicular activities. We found seven settings in which color coding is used. The table below summarizes our findings, which are detailed in Appendix A.

Setting	**Color Coding...**
Computer operations	Always redundant
Location coding	Always redundant
Controls (general)	Always redundant
Controls (specific)	Always redundant
Caution and warning system	Always redundant
Displays	Always redundant, except: • LEDs*
Cables and connectors	Always redundant, except: • single-conductor wires • connectors*

* *Must conform to [5(§9.5.3.2.i)]*

We conclude that the vast majority of color coding within NASA vehicles uses color as a redundant cue.

Before judging the potential difficulties caused by the non-redundant uses of color shown in the table, NASA's limits on color coding must be understood.

Restrictions on Color Coding. In general, color coding in NASA space vehicles must adhere to the standards in [5(§9.5.3.2.i)]. This paragraph has several subparagraphs, requiring:

1) Only one hue within a color category (e.g., red, green) shall be used in a give coding scheme.

2) No more that 9 colors, including white and black, shall be used in a coding system.

3) Color coding shall not be used as a primary identification medium if the ambient light is variable or if the operator's adaptation to ambient light varies. (This would presumably apply to all devices on the shuttle flight deck or near a space station window.)

4) Color meanings should be consistent with common usage (e.g., red indicates "stop" or a problem).

5) **"To avoid confusion by color-deficient observers**, do not use the color green if the color scheme uses more than six colors." (Emphasis added.) Additional requirements pertain to avoiding confusion for color-deficient observers when less than 6 colors are used.

6) not applicable

7) not applicable

8) List of 9 colors that are safe for color deficient persons.

This is a remarkable list of requirements. It shows that, although NASA has never (knowingly) hired a color defective astronaut, color coding aboard NASA space vehicles is designed to accomodate them. Because of this color coding standard, in two of the table's three cases in which color coding is non-redundant, color deficient astronauts will not be disadvantaged.

Single-conductor wires. Please consult Appendix A for details. We are not sure this use of color coding actually exists aboard NASA space vehicles. If it does and if it does **not** conform to the requirements of [5(§9.5.3.2.i)], then a strategy like that in section 3.3 may be used.

3.2.3 Shuttle and Space Station – Exterior operations

As we turn our attention to operations outside the spacecraft, several comments are in order:

a) The policies and requirements governing the use of color in the interior, discussed in the previous section, are valid for operations outside the spacecraft.

b) Windows on NASA spacecraft and visors on EVA space helmets are both neutral density, i.e., they do not alter colors.

c) Color coding is unlikely to be used extensively in extra-vehicular environments because of the large, frequent changes in ambient light in low earth orbit.[1] NASA design requirements state: "Color coding shall not be used as a primary identification medium if the ambient light is variable" [5(§9.5.3.2.i.3)]

That said, there is one scenario in which color may be used in exterior operations: orientation lights on other space modules.

The specification for orientation lights is given in figure 8.5.3.3-1 of reference [5]. We are going to examine three facets of orientation lighting: (1) nonchromatic cues, (2) chromaticity, (3) operational scenarios.

Nonchromatic Cues. Orientation lights provide significant information using nonchromatic cues: (a) the green (starboard) light is more than

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[1] The shuttle's orbital period is roughly 90 minutes, meaning there is both a sunrise and a sunset every 90 minutes.

twice as bright as the other orientation lights, and (b) the forward position is indicated by dual lights.

Chromaticity of Orientation Lights. Four colors are used for orientation lights: red, green, yellow, and white. The chromaticities for each color are plotted in the diagram below, as are the chromaticities of the Falant's lights.

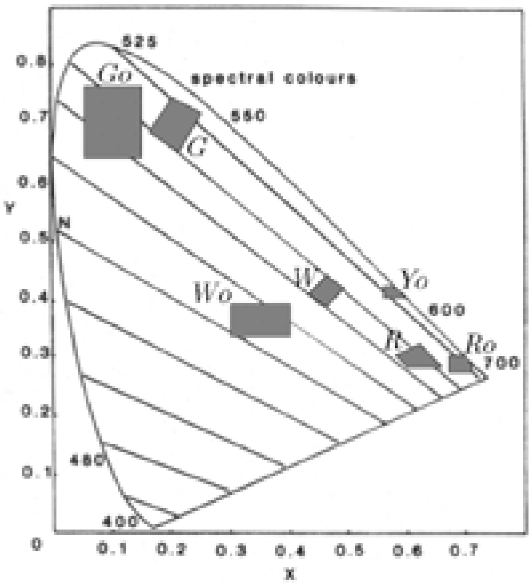

Figure 3-1. Color coordinates for the orientation lights mandated by NASA: Ro = red, Go = green, Wo = white, Yo = yellow. R, W, and f represent the red, white, and green lights, respectively, used in the Farnsworth lantern.

It is immediately apparent that NASA's space module orientation lights are easier for deuteranopes to distinguish than are the lights used in the Falant. The Falant lights lie almost exactly on a deuteranopic color confusion line (this is deliberate, of course), while the NASA orientation lights do not. Deuteranopes will have difficulty distinguishing the red from the yellow orientation light strictly on the basis of hue, but other cues are available, however: yellow light is perceived as brighter than red light.

Operational scenarios. Casual examination suggests that the task of determining the attitude of an approaching space vehicle seems to be similar to the Navy's canonical task of judging colored lights at sea. There are several major differences, however:

a) Redundancy. Orientation lights will not be redundant when either (1) it is dark and the overall form of the module is not visible, or (2) it is light, but there are so many axes of symmetry on the space module that it is not possible to distinguish its orientation using the module's form. We will dismiss the second possibility. The first possibility is also unlikely, given that NASA strongly prefers to schedule critical phases of orbital rendezvous for daylight conditions.

b) Distance. For a mission specialist, interaction with other space modules occurs at close-in distances. To date, the Manned Maneuvering Unit (MMU) has been flown only to a distance of approximately 300 feet [5(fig. 14.7.4.1-1)] and the Shuttle Remote Manipulator System, a.k.a. "The Arm," can extend itself a maximum of 50 feet [5(§14.7.4.2)]. In darkness at these ranges, a simple flashlight would provide enough illumination to answer questions about the orientation of the other module.

c) Tempo. Orbital operations are slow and deliberate, slower even than maritime speeds and aerial refueling. The following table shows maximum closing speeds in various settings.

Environment	**Maximum Closing Speed**
Aviation	1200 mph
Driving	150 mph
Maritime	50 mph
Manned Maneuvering Unit	0.5 mph/sec (acceleration) [5(fig. 14.7.4.1-1)]

Of note, very slow relative speeds opens the possibility of the autokinesis effect, which would support the use of lighting stripes instead of pinpoint lights.[2]

Conclusion. We have seen that orientation lights carry information nonchromatically. We have calculated that even deuteranopic mission specialists will likely be able to recognize all but one of the orientation lights used in external space modules. We have seen that orientation lights are redundant during daylight, when orbital rendezvous are preferentially

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[2] The autokinesis effect occurs when pinpoint lights, e.g., navigation lights, are the only thing visible in darkness. Even though the lights may be unmoving in space, the brain will, after awhile, impart motion to them. This can be a problem in formation flying or for refueling boom operators. The Air Force outfitted the F-4 Phantom II with formation light stripes to get around this problem.

scheduled. We have also seen that the distances at which mission specialists become involved in operations with another space module are small, at a range where orientation lights become redundant even in the dark.

Thus, operations outside of NASA space vehicles do not demand normal color vision.

3.3 Color filters

Colored filters allow a color deficient person to make any color discrimination a color normal person can. But, just as there is no single refractive lens that enables a presbyopic person to focus at all distances, there is no single color filter that enables a color defective to distinguish all colors in all situations.

Although we have discovered no situation in which it is necessary, let us suppose a deuteranope must discriminate two colors that lie on his color confusion lines. There are two general approaches available [1(p. 39)].

Brightness Alterations. If colors X and Y, of equal brightness, are confused by a deuteranope, then an X-colored filter may be used to distinguish them. Viewed through the filter, the X-colored object will look bright and the Y-colored object dark (because no Y color gets through the X-colored filter).[3]

This technique has allowed color defectives to identify color coded resisitors and helped color defective students learn histology [1(p. 39)]. Of note, after failing the Falant at NASA JSC with unaided vision, the author was able to get a perfect score by using red and green filters mounted in spectacle frames.

Saturation Enhancement. All humans find it more difficult to discriminate desaturated, "washed out," colors than saturated colors. In color-normal persons, yellow-tinted glasses enhance color saturation by removing the part of the spectrum that tends to wash out colors. These glasses do not work for deutans, however, because a different part of the spectrum, the blue-green, desaturates colors for them [1(pp. 30-31)].

Magenta filters absorb all wavelengths from blue-green to green, and pass wavelengths at both ends of the spectrum. Thus, for deutans, magenta glasses enhance color saturation by reducing the spectral wavelengths that would only act to desaturate the color of an object. The resulting colors are more vivid and are more easily distinguished [1(p. 39)].

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[3] Of course, a Y-colored filter could also be used to distinguish the two colors.

3.4 Color perception in scientific experiments

Conceivably, a scientific investigation could call for the astronaut to visually assess the color of a reagent, organism, or apparatus. This is not a concern because it represents poor science, if for no other reason than it is irreproducible. Given the plethora of cameras and other recording devices on every NASA space mission, it is difficult to believe that anything escapes being photographed.

Additionally, there are a number of scientific instruments which, at their core, do nothing but measure color. A scientist who believes color is important is going to include one of those devices in the experiment.

3.5 Color vision in other transportation industries

Given that space travel is but one type of transportation industry, it would be instructive to examine the experience of color defective workers in other transportation industries to see if there are problems of safety or mission accomplishment. Appendix B discusses, in detail, whether congenital defects of color vision confer increased risk in any form of transportation in which color coding is used (rail, maritime, aviation, driving). Here, we mention just the highlights.

Color vision standards have been used in the transportation industries since the late 1800s. Thus, the findings of Cole and Vingrys, who in 1988 reviewed the literature relating defective color vision with transportation accidents, seem unsurprising at first: They found no case after 1891 in which they were confident a congenital defect of color perception caused the accident [83].

The results of Cole and Vingrys become surprising, however, after realizing that almost all color vision tests used in the transportation industries are significantly deficient in either their design or execution:

a) Since 1875 the Holmgren Wool test has been a standard test for color vision in many national railway systems. It was adopted by the British Board of Trade in 1895. It is still the favored test in some industries. A modern examination of the test, however, shows that it simply does not detect red-green color deficiency [12].

b) In the 1970s the US Air Force acknowledged that, due to widespread improper color vision testing procedures, “about 25% of color defectives passed undetected into flying training” over a period of decades

[74].

c) In a 1966 review of the Falant's performance, the US Navy acknowledged that 15-20% of color defective persons were not being eliminated [61(p. 9)].

d) Although the Air Force and Navy studies have not been recently repeated, there are clearly still problems, as illustrated by the US Naval Academy's intermittent quality control difficulties with pre-enrollment color vision testing of its midshipmen [34].

e) The FAA's pre-1996 color vision standard has been described thus: "anyone with defective colour vision can obtain an unrestricted pilot's license if they are persistent enough" [20]. Australia has had no color vision requirement for civil aviation since 1989 [2].

f) The lantern tests used before World War 2 by many navies and maritime agencies were so confusing to both examiner and examinee that the results of testing were not interpretable [30].[4]

g) In 1946 Farnsworth wrote: "There are today at least hundreds of men of more or less professional standing, and even 'schools', who for the sum of $5 up to $50 or more will guarantee to train men so that they can pass the pseudo-isochromatic plates used in examination for military service" [31].

Thus, color defective men have, for a very long time, and in large numbers, been filling transportation and military jobs in which they supposedly posed a danger. Yet, there is no evidence showing the danger ever materialized.

Here is a revealing example of the non-danger. Given that large numbers of color defective men likely entered flying training in the US Air Force and US Navy, I queried the medical safety archives of both services for color-related mishaps. The two archives contain only one relevant mishap: a near-miss involving a color defective fighter pilot in the landing pattern at twilight. Color deficiency was designated as contributory, but not causal. It was thought that properly perceived colored navigation lights on the other aircraft could have alerted the pilot earlier to the other aircraft's course.[5]

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[4] For example, with the Eldridge-Green lantern "the test often resolves into a contest of color-naming wits between doctor and applicant; and, if the diagnosis is unfavorable, the applicant goes shopping for a doctor who will pass him" [30].

[5] Even if we accept this argument, this incident involved two vehicles with a relative velocity of perhaps 500 knots. For the past 40 years the US space program has not

Color vision and driving present another fascinating story. Driving is interesting to us for two reasons (1) split-second decisions can avert (or cause) a crash, and (2) tens of millions of color deficient men drive every day.

Most authorities conclude that deutan drivers are not at increased risk [e.g., 79], yet a few disagree and even call for restrictions on driving by color deficient persons [21]. All agree that none of the multiple studies on the subject have produced an unassailable answer. Interestingly, the failure of multiple studies to prove that color deficient drivers are at increased risk is a telling point, given that investigators have recently had no difficulty proving the following:

a) Using a cellular telephone while driving confers risk [65].

b) Smoking while driving confers risk [69].

c) The switch to daylight savings time confers risk [24].

d) Having a current benzodiazepine prescription confers risk [10].

Finally and most importantly, there is no automobile insurance company that charges lower rates for color-normal drivers or higher rates for color-defective drivers. Yet they all immediately charge higher rates for two years after a speeding ticket, and do so based on a mountain of supporting statistical evidence. This is a lesson of immense value: **whatever the risk of defective color perception in the transportation industry, it is clearly lower than the risk conferred on a driver by a single speeding ticket**.

3.6 Other standards

3.6.1 Military

Submarines. Much of the original work on color vision standards came from the US Naval Submarine Medical Research Laboratory (NSMRL) in Groton, CT, where the Falant was invented [31]. Since 1954, anyone unable to pass the Falant has normally been prohibited from serving in the submarine corps. The NSMRL justifies this requirement with the fact that

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conducted space operations between vehicles at that kind of velocity, and will not for the next 40.

"judging colored lights at sea [is] the most critical color-related task that Naval Officers perform" [48].

The NSMRL requirement is, however, flexible. "In times of critical need for specific specialties, waivers can be considered for men of exceptional ability and motivation" [48]. The experience with such waivers has been positive:

> During the past three to four years, three men have served on submarines under a waiver of the color vision requirement... The Commanding Officer and other supervisors reported that the color vision deficiency did not degrade the performance of the color defectives aboard the ship. The color defectives themselves, however, did report occasional difficulty in correctly identifying navigational lights on intial observation, but stated they that they exercised extreme diligence in keeping their eyes on the lights as the target neared.... It is felt that a major reason for the lack of severe problems lies in the fact that the men were aware of their special status. It cannot be emphasized too strongly that the man who admits his defect, realizes he cannot distinguish colors and seeks help does not represent the same hazard as the man who hides his defect and attempts to perform normally. [48]

The NSMRL experience is important in re-assessing the MS deutan standard. Identification of distant signal lights is far less important for mission specialists than for submariners. Despite the importance of the task, NSMRL is willing to waiver color deficiency, suggesting the NASA MS deutan standard is too strict. That closing speeds in the maritime environment are much faster than closing speeds in orbital operations corroborates this.

USNA. "For a very few color-deficient candidates whose records reflect truly extraordinary leadership potential," a color vision waiver is available for the US Naval Academy [34].

USA, USMC. We have not recently investigated the standards for color vision in US Army or US Marine Corps ground units, although it appears that there is no requirement [34]. The issue is germaine because some aviation authorities have concerns over map-reading by color deficient pilots. In the mid-1970s, at least, a high school student could be awarded a Marine Corps ROTC scholarship for the infantry even after failing the Falant. The Australian court dismissed concerns about map reading and color vision [2(§73)].

3.6.2 Civilian

FAA. The FAA changed its requirement for color vision in 1996. Previous standards had required "normal color vision" for first-class certificates and the ability to distinguish aviation signal gun colors for second- and third-class certificates [32(P-59)]. In practice, failure on the pseudoisochromatic plates required that any medical certificate issued be limited, prohibiting flying at night or by color signal control. Passing a "practical" test using the sigligun (signal light gun) or passing a medical flight test would lift the limitation [32(P-59)].

In 1996, the standard for all three classes became uniform: "the ability to perceive those colors necessary for safe performance of airman duties" [32(§67.103.c, §67.203.c, §67.303.c)]. The regulation provides little additional detail, saying only that "the FAA wil provide guidance to Aviation Medical Examiners to assist in these tests" [32(P-59)].

During the comment period before the rule was issued, 79 of the 80 comments received by the FAA generally supported the new standard [32(P-51)]. Interestingly, the Aerospace Medical Association suggested that the FAA not perform color testing of persons who fail pseudoisochromatic plates, and instead base the standard on an individual's ability to perform safely [32(P-59)].

Australia. Just before the courts struck down Australia's standard for color vision in civil aviation [2], the following scheme was proposed [85]:

1) Administer pseudo-isochromatic plates. Failure leads to step 2.
2) Classify defect using anomaloscope or OSCAR. Deutans go to step 3.
3) Administer Falant. Pass if **six** or fewer errors.

Passing the Falant would allow the pilot to fly at night. This would allow two-thirds of color defectives to fly at night, which is similar to the rate allowed by the FAA's Falant/Sigligun combination [85]. There was no restriction contemplated for daytime flying in Australia.

3.7 Summary

This is the most important chapter in the document. We have seen that NASA has flown a color deficient astronaut, apparently successfully. His success should not be a surprise, because the non-redundant use of color in aviation and space operations is extremely limited. NASA space vehicles, in fact, are engineered to be safe for color deficient crew members. Furthermore, color deficient crew members can be equipped to make any color distinction. Experience outside the space program, in other transportation industries, is confirmatory: color deficiency is not a threat to safety or mission accomplishement.

We conclude that the absolute risk of eliminating the MS deutan standard is undetectably small.

Chapter 4

Relative Risks of Relaxing the Standard

As we have seen, the risk of relaxing the MS deutan standard is not demonstrably greater then zero. Yet, it is not surprising that the standard remains overly restrictive. There is a natural tendency to believe that "If military aircraft are becoming larger, more expensive, faster, and fewer in number, why should we select their captains with physiologic deficits of any kind?" [74].

Fortunately, and commendably, NASA does not follow this approach. There are many physiologic deficits and risky habits that are acceptable in the astronaut corps. This section reviews a limited number of allowable deficits so the reader can get a feel for the level of risk NASA deems acceptable.

In no way should criticism be read into the discussion of these standards. The sole purpose in presenting them is to show that NASA medical standards are not zero-risk.

4.1 Visual acuity

The visual acuity requirements for NASA astronauts have been progressively easing. The current near-vision requirement is 20/200. Without doubt, this relaxation is the culmination of many different inputs, including the increasing experience with myopic astronauts who perform their duties satisfactorily.

In most states, 20/200 is defined as legally blind. Astronauts with this degree of visual impairment (and many with substantially less) are absolutely dependent on their eyeglasses to perform normal crew functions. Whether they are absolutely dependent on their eyeglasses to perform emergency functions is a key question.

There have been a number of papers in the medical literature asking "What do color blind persons see?" [42(p. 452-455), 80] and attempts by physiologists to computationally model the appearance of the deutan world [2, 15, 75]. Of course, there are no articles in the literature asking "What do myopes see?" – but we can all get the answer by wearing distorting lenses or waking up in the morning with eyelids more stuck together than usual. With the benefit of having experienced both worlds, I can tell you it is incalculably easier and safer to function unaided in the deutan world than in the myopic world.

4.2 Sickle cell trait

Persons who carry two copies of the gene for sickle hemoglobin experience the devasting disease called sickle cell anemia (HbSS). Persons who carry one copy of the sickle hemoglobin gene and one copy of the normal "A" hemoglobin gene have sickle cell trait (HbAS). The prevalence of sickle cell trait in people of African descent is high, averaging 20-30% in west Africa, and reaching 45% in some regions of east Africa [13(pp. 191-193)]. The prevalence in African Americans is 10% [36], which means 3.5 million Americans carry the gene.

Contrary to popular belief, sickle cell trait is not a benign condition, especially in the aerospace environment. Serious complications, such as splenic infarction and/or acute abdomen, can occur when these persons fly in unpressurized aircraft at an altitude of just 10,000 feet [33]. In 1955 Smith and Conley presented a series of 12 such patients [71]. In another series, 6 men with sickle cell trait developed acute abdomen due to splenic infarction within 48 hours of arrival in Colorado from lower altitudes [46].

Violent exercise at an altitude of just 4000 feet has been reported to precipitate sickling crises in persons with sickle cell trait, leading to sudden unexpected death [41]. Based on data from recruit training in the US Armed Services from 1977 to 1981, Kark et al [43] calculated that sickle cell trait carries a relative risk of 27.6 for sudden unexpected death for blacks during enlisted basic training.

For these reasons, sickle trait was physically disqualifying for pilot training in the US Air Force until at least the 1970s.

Today, both NASA and the US Air Force accept candidates with sickle cell trait, despite the the significant risk such persons would face in a prolonged decompression situation. The risk may be acceptable in aviation, where descent is always an option within one or two hours. In space, however, the rapid descent option is absent or significantly impacts mission objectives. We conclude that the risk of allowing astronauts to have sickle cell trait is substantial.

4.3 Jewelry

U.S. Air Force and Air National Guard combat aircrew always remove “rings and rags” before stepping to the aircraft. NASA spacecrew members do not follow the same practice in the space shuttle. A NASA videotape shows astronauts wearing not just wedding and other rings, but necklaces, too [57 (time stamp=10:38)].

Given the unfamiliarity with movement in microgravity among rookie crewmembers, and the cramped quarters in general, the opportunity to catch a piece of jewelry on a piece of equipment seems substantial.[1]

4.4 Physical strength

It is hard to imagine a scenario in which a small weak astronaut would be a more desirable crewmember than a big strong one. Astronauts perform numerous routine and emergency tasks in which physical strength is an asset or a requirement. Yet, there is no physical strength requirement in the NASA medical standard, and NASA accepts astronauts over a large range of size and strength. (When I interviewed in 1989, we were given strength tests, but were told they checked only for symmetry.)

NASA does not assign a 100 lb. astronaut to extravehicular activities that involve grabbing and holding a rotating satellite. Instead, it sends the guy nicknamed “Ox” (James van Hoften, STS-41C, 1984). This simple, commonsense deployment of resources refutes the claim that NASA considers all its astronauts to be interchangeable parts, and that any member of the corps should be capable of being assigned to any duty. Even with all the weightlifting in the world, a 100 lb. woman can no more affect her maximum

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[1] The risks of this practice would not be lost on Neil Armstrong who, a few years after returning from the moon, jumped from a pickup truck, caught his wedding band on a part of the truck, and avulsed his left ring finger in the process. The finger was successfully reattached.

strength in comparison to Ox's than a deuteranope can ever affect his color vision in comparison to Ox's.

4.5 Cigarette smoking

Several of the original Mercury 7 astronauts were smokers. The prevalence of smoking in the astronaut corps today is not published. Using the Framingham equation, it is possible to estimate the attributable cardiovascular mortality risk of cigarette smoking.

A 40 year old man with a systolic blood pressure of 120 mmHg, a total cholesterol of 180 mg/dl, and an HDL cholesterol of 45 mg/dl has a 5.1% chance of dying a cardiovascular death in the next 10 years if he is a smoker. The risk is 2.7% if he is a nonsmoker. The attributable risk of cigarette smoking is thus 5.1-2.7=2.4% over ten years.

Given that sudden death is the first symptom of coronary artery disease in 20% of cases,the risk of a sudden unexpected cardiovascular death attributable to cigarette smoking is approximately 0.5% during the ten years. If we assume a 100 day space station mission, then an astronaut who smokes adds about one chance in 10,000 that there will be a sudden cardiac death during the mission.

4.6 Geriatric cardiology

Senator Glenn's recent flight aboard STS-95 carried a substantial amount of medical risk. Subclinical coronary artery and cerebral artery disease are extraordinarily common in persons of his age, and can be definitively ruled out only by invasive studies. Autonomic reflexes, which control blood pressure and heart rate in response to changes in posture (gravity), are subject to aging. To convincingly demonstrate that these reflexes are normal would require a battery of tilt-table and drug infusion tests which are not part of the routine NASA flight physical.

The most inescapable cardiovascular consequence of aging, however, is a decline in aerobic capacity – an integrative measure of the cardiac, pulmonary, and muscular systems' ability to do physical work. Decline in aerobic capacity is inevitable, no matter how much a person exercises. The graph below predicts that Senator Glenn's aerobic capacity, measured by maximum oxygen uptake, is only 30% of what it was when he was 30 years old.

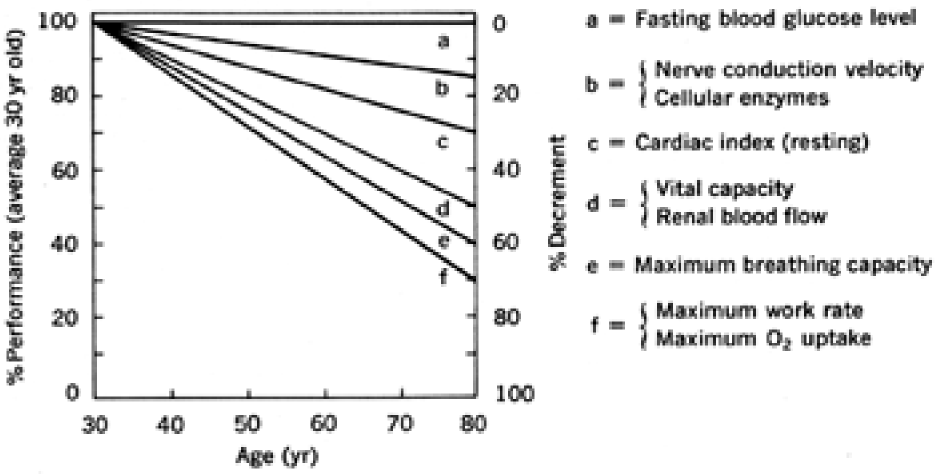

Figure 4-1. Decline in various physiological functions with age [52(p. 1991)].

The minimum aerobic capacity needed to successfully perform astronaut duties is probably unspecified. However, as others have commented without recourse to cardiovascular physiology [53], the lower the performance that is accepted, the higher the risk.

4.7 Summary

This chapter has shown that NASA does not operate at a level of zero medical risk. Thus, it is not consistent with NASA policy to insist that relaxing the MS deutan standard be a zero-risk prospect.

The previous chapter showed that the risk of eliminating the MS deutan standard is extremely small. By comparison, the example of sickle cell trait in this chapter has shown that NASA's level of acceptable medical risk is substantial.

Chapter 5

Flaws in the Current Standard

The largest potential flaw in the current color vision standard would be a mismatch between the color demands of the standard and the color demands of the mission specialist's job. This section discusses other types of flaws in the current NASA color vision standard.

5.1 Color vision tests vs. the real world

Color vision tests are useful only to the extent they predict a person's ability to perform a real-world color task. On this topic, the chief of the Vision Branch at the US Naval Submarine Medical Research Laboratory (US NSMRL) has written:

> Attempts to correlate the results on a specific color task with scores on color-vision tests or with classifications of the men according to degree of defect are frequently disappointing [44].

The results of several studies support this conclusion, including:

a) "Neither the anomaloscope range nor quotient gives any indication of the ability of color defectives to recognize colors of traffic lights" [54].

b) Steen et al [72] tested 137 color defectives on a Nagel-type anomaloscope and the aviation signal light gun. While, on average, persons with better scores on the anomaloscope better judged the lights on the signal gun, there were some men in every category, from mild to dichromatic, both protan and deutan, who scored perfectly on the signal gun.

c) Within every degree of color deficiency (as assessed by Hardy-Rand-Rittler pseudoisochromatic plates), some men were able and some men were unable to name red and green point light sources of various illuminations [70].

d) A small proportion of color-normal navy look-outs suffer from a significant disability in the perception of distant signal lights and are unfit for the task [83(p. 266)].

The US NSMRL conducted its own study to investigate this phenomenon [44]. They took 81 color-defective and 24 color-normal men, assessed their degree of color deficiency in the laboratory with a battery of color vision tests, then asked them to judge the color of ship running lights at distances of 1, 2, and 3 miles. The results:

- On average, the mildly defective men did better at judging the lights than the other color defectives, but "there was no systematic degradation of performance with increasing degree of defect."
- 11 of the color defectives did as well or better than the 3 worst color normals.
- 26 color defective men did better than the worst color normal. These 26 men came from all three grades of deutan (mild, moderate, severe) and from the mild protan group.
- Statistically, the Falant did correlate with the ability to judge lights at a distance, but "the correlation is too small to be useful for selection."
- "Once again the major finding of interest is the inability to predict with certainty, despite the careful pre-screening, which men will do well in the practical situation and which will not."

Color vision researchers have been unable to explain the failure of testing to predict real-world performance. According to the NSMRL group, "it appears there is another factor operating to produce these extremes in performance that is not being adequately assessed" by the battery of color vision tests [44].

Identifying these extra factor(s) is a challenge for the next generation of color vision researchers. The human eye-brain system is so complicated and robust that we should be surprised if its performance could be described by a few simple laboratory tests.

5.2 Falant technical issues

Color selection. Even if one accepts the Falant as a predictor of real-world color performance, there are still reasons to believe it does not give information about the examinee's ability to judge aviation signal lights. In designing his lantern, Farnsworth needed to pick a single set of three colors which lay on confusion lines for both deutans and protans. In doing so, he chose a red which was outside the boundaries set for red aviation signal lights by the ICAO (International Civil Aviation Organization) [85].

Unfortunately, the only study examining whether this makes a difference was so poorly designed that it is impossible to draw useful conclusions [85]. Zentner recommends, however, that if the Falant is used, the red filters should be selected to fall inside ICAO color boundaries [85].

We have already seen that the chromaticities on the Falant do not match the chromaticities specified by NASA for space module orientation lights (section 3.2.3).

Speed. Because each inductee is medically examined before entry into the US Armed Forces, military medical establishments find themselves under great time pressure to complete all their assigned medical examinations. As a result, clinical tests used by the Armed Forces must be simple and rapid, characteristics which make the pseudoisochromatic plates and the Farnsworth lantern appealing.

NASA, however, finds itself in a different position. Its candidates are present in Houston for an entire week and are much more highly selected than the Armed Forces. Although time is not available in vast quantities, there is no requirement that medical tests be simple or rapid. As we have seen, there have been compromises made in the Falant in the name of speed (i.e., the fact it can be used for both protans and deutans). NASA should not feel compelled to adhere to a standard because of logistics.

5.3 Protanopia and the Falant

Protan subjects will fail NASA's first line test for color vision, the pseudoisochromatic plates. The subjects will then have the Falant administered. Although the original research from Farnsworth's laboratory claimed that the Falant fails protanopes and most protanomalous subjects [31, 47], subsequent experience disputes this [81, 85]. Reference [4] contains the report of a protanope evaluated at the USAF School of Aerospace Medicine who, on three separate occasions, was able to get a perfect score on the Falant.

It is unclear why protans are able to pass the Falant. Of note, the specification for the Falant includes an extra 5% brightness for the red light so that protans will not be able to use subjective darkness of the red light as a distinguishing cue [31].

5.4 Protanopia and perception of red light

Protan defects are associated with a reduced ability to perceive red light. That is, in some situations, normals and deutans will recognize that a light is present whereas a protan will not. This could be a safety hazard above and beyond the ability to determine the color of a light.

Generally, it is the protanopes and the more severe protanomals that have difficulty seeing red lights [2]. It is unclear how often milder protanomals, i.e., the ones who pass the Falant, have the raised threshold for detecting red lights.

The current NASA testing procedure does not categorize the color vision defect in persons who fail pseudo-isochromatic plates but pass the Falant. It would seem prudent to identify protans who do this, and formally assess their ability to perceive red light.

5.5 Uncorrected color vision

For reasons unclear, the current NASA color standard requires that the Falant be passed with *uncorrected* vision. In fact, visual acuity has a major effect on color perception. Myopes with normal color vision can fail the Falant without their corrective lenses [61(p. 12)]. The NASA standard may be referring to vision that is not color-corrected.

Of note, the minimum angle of resolution for a person with 20/400 vision is 20 minutes of arc [40(p. 2)]. The angular separation between the two lights on the Farnsworth lantern at the normal 8-foot test distance is 18 minutes of arc [31, 81].

5.6 Brandenstein redux

To the extent that persons with congenital defects of color vision are discovered after they have already passed the standard color vision tests, the standard tests must have been administered incorrectly (see section 3.1).

5.7 Summary

We have discovered the dirty secret of the color vision world: laboratory tests of color vision do not predict an individual's ability to perform real-world color tasks. We have also discovered several flaws in NASA's current gold standard, the Falant: it does not test the ability to recognize aviation red signal lights and it does not reliably detect protan defects. The NASA color standard is ambiguous with regard to "corrected vision," and there is at least one example where the tests were administered inadequately.

Chapter 6

Benefits of Relaxing the Standard

Although it may seem odd to mention possible benefits of a color vision defect, it is actually quite logical. Like sickle cell trait and cystic fibrosis trait, color deficiencies would not have reached their extraordinarily high prevalence unless they conferred a significant survival advantage to primitive humans.

6.1 The camouflage effect

The following discussion is taken from the article by Morgan et al [51], which offers experimental proof of the well-known Army lore that color-deficient observers can penetrate camouflage which deceives a normal observer. There are 2 possible mechanisms for this capability:

(a) "If target and background reflect physically different fluxes that match for the normal eye (i.e. are 'metameric') they may well look different to the anomalous trichromat, whose retina contains at least one type of receptor that is abnormal in its spectral sensitivity."

(b) Color defectives "can readily detect boundaries between textured regions under conditions where such boundaries are missed by the normal observer. By offering a rival perceptual organization to the normal eye, random color variation can impede the pre-attentional segregation of textural boundaries, but [color defectives] are unaffected by this colour variegation, even when it represents for them a substantial random variation in luminance."

Mechanism (a) is the inverse of pseudo-isochromatic plates: Pseudo-isochromatic plates, of course, can make objects "invisible" to anomalous trichromats when viewed under very specific lighting conditions. Similarly, camouflage can make objects "invisible" to normal trichromats when viewed under certain lighting conditions. Mechanism (a) is readily demonstrated by the pseudo-isochromatic plates in which color defectives can see a number, but normal trichromats cannot (e.g., Ishihara plates 14 and 15 [34]).

In their paper, Morgan and colleagues experimentally demonstrate that mechanism (b) exists in dichromats. They show that dichromats are superior to normal trichromats when it comes to detecting boundaries between textured regions.

Morgan et al speculate that, like Army platoons, primitive foraging groups may have benefitted by having a diversity of perceptual abilities in their group. The same could no doubt be said for space crews.

6.2 Speculative advantages

6.2.1 Mesopic lighting

Reimchen [66] made the fascinating observation that the prevalence of color defects among indigenous peoples increases with distance from the equator. He notes that the length of twilight also increases with distance from the equator, and presents weak evidence suggesting that a deutan visual system may operate more efficiently than a normal one at twilight.

Interestingly, Verriest et al [79] studied deutan drivers under a variety of conditions and found that, under overcast skies, deutan subjects were sometimes able to recognize brake lights from a greater distance than normals.

Such an effect is biologically plausible. As illumination decreases, cone-mediated vision yields to rod-mediated vision. During this transition, color vision will begin to be unreliable, so persons who normally depend heavily on color cues may be at a disadvantage, whereas those unaccustomed to using color cues may be at an advantage [2(§44, §73)].

6.2.2 Operations in a vibrating environment

On some American spaceflights vibration has been severe enough to degrade the readability of dials and displays, especially during liftoff and landing [5(§5.5.2.1.1)].

It is thought that the visual system's critical flicker frequency (CFF) affects the readability of displays in a vibrating environment: the higher the astronaut's CFF, the more vibration can be visually tolerated [5(§4.2.2.b)].

Several studies have found that deutan defects are associated with a higher CFF and a more rapid visual integration time [6, 25, 35]. The difference is most pronounced for red stimuli [35]. The effect is biologically plausible because (1) color pathways are slower than luminance pathways [1(p. 19)], and (2) the temporal resonance of individual cones accounts for the variation in human CFF [1(pp. 7, 15)]. It is thought that color vision evolved to be more sensitive to large, slowly changing objects [1(p. 19)].

Thus, in a severely vibrating environment, deutan astronauts may be better able to read dials and displays than normals.

6.3 Scientific advantages

Accepting color weak persons into the astronaut corps expands the possible investigations of human color vision that may be coducted in space. For example, the Soviets, using questionable techniques, have reported changes in color perception shortly after entry into orbit [76]. Americans have not confirmed this [5(§4.2.2.f)] and have not been overly concerned because there is no biologically plausible mechanism by which such changes might occur.

Specifically, the Soviets report a lowered efficiency in perceiving green – a deutan defect.[1] A deutan subject, serving as a control, could be useful in investigating this effect. As Kaiser and Boynton note, some of the most important advances in understanding human color vision have developed from the study of color defectives [42(pp. 441-442)].

6.4 Societal benefits

6.4.1 Legal issues

The Americans with Disabilities Act (ADA) was enacted in 1990. Although it does not apply to the civil service, hence NASA, it presumably reflects the desire of the American people that persons with physical defects should enjoy the same access to jobs as persons without those defects. Americans certainly want access to take a back seat to safety, but the message is clear: when it's a dead heat, access should win.

The Rehabilitation Act of 1973, upon which the ADA was based, does apply to the civil service, however. Based on this, one of the ADA's co-

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[1] It would be ironic if all space travelers are deutan and that a deutan person may perceive colors in space as well as a normal!

authors has gone so far as to say that the Brandenstein precedent makes it illegal for NASA to refuse employment as an astronaut due to defective color vision [59].

6.4.2 The talent pool

We have said little about the epidemiology of color vision defects. The table below summarizes the data:

Population	**Defect**	**Prevalence**	**Ref.**
Western European	any	8%	[50, 45]
Western European	deutan	6%	[50, 45]
Western European	protan	2%	[50, 45]
US Military	any	10%	[62]
US Military	fails Falant	7%	[44, 62]

(In some Scottish communities 25% of the men and 9% of the women have a color deficiency [19, 37]!)

Among the classical phenotypes in a Western European population, the breakdown is as follows [55]:

deuteranomalous	57%
deuteranopic	16%
protananomalous	12%
protanopic	15%

Applying these statistics to the 132 million men in the United States [18], we can estimate that the current NASA color vision standard removes approximately 8 million people from the potential astronaut talent pool. Eliminating the deutan standard altogether would add 6 million people to the potential pool immediately. The benefits are obvious.

6.5 Summary

We have seen several reasons why relaxing the MS deutan standard would benefit NASA and its space crews. There are some situations in which the color defective's visual system is superior, and having more than one type of visual system aboard increases the amount of information available to the crew. Having a color defective in space enhances any scientific studies of the color vision system that may be performed.

Aside from biological reasons, relaxing the standard is in keeping with the mood of the United States, removes the potential for noncompliance with the law, and adds millions of people to the pool of talent from which NASA can draw astronauts.

Chapter 7

Summary and Recommendations

We summarize the findings of chapters 3-6 of this document:

Absolute Risk. NASA has flown a color deficient astronaut, apparently successfully. His success should not be a surprise, because the non-redundant use of color in aviation and space operations is extremely limited. NASA space vehicles, in fact, are engineered to be safe for color deficient crew members. Furthermore, color deficient crew members can be equipped to make any color distinction. Experience outside the space program, in other transportation industries, is confirmatory: color deficiency is not a threat to safety or mission accomplishement.

We conclude that the absolute risk of eliminating the MS deutan standard is undetectably small.

Relative Risk. NASA does not operate at a level of zero medical risk. Thus, it is not consistent with NASA policy to insist that relaxing the MS deutan standard be a zero-risk prospect. The example of sickle cell trait shows that NASA's level of acceptable medical risk is substantial.

Flaws in the Current Standard. Laboratory tests of color vision do not predict an individual's ability to perform real-world color tasks. We also discovered several flaws in NASA's current gold standard, the Falant: it does not test the ability to recognize aviation red signal lights and it does not reliably detect protan defects. The NASA color standard is ambiguous with regard to "corrected vision," and there is at least one example where the tests were administered inadequately.

Benefits of Relaxing the Standard. There are several reasons why relaxing the MS deutan standard would benefit NASA and its space crews:

There are some situations in which the color defective's visual system is superior, and having more than one type of visual system aboard increases the amount of information available to the crew. Having a color defective in space enhances any scientific studies of the color vision system that may be performed. Aside from biological reasons, relaxing the standard is in keeping with the mood of the United States, complies with the law, and adds millions of people to the pool of talent from which NASA can draw astronauts.

Recommendation. The following standard for color vision in mission specialist applicants is recommended. Note that, like the current standard, it ignores the possibility of tritan (so-called "blue-yellow") defects. Also, like the current standard, it assumes that complete and detailed ophthalmological and physical examinations are performed.

(1) Pseudo-isochromatic plates are administered first. Examinees earning a passing score are judged to have adequate color vision and no further testing is performed. Examinees who do not earn a passing score go to step 2.

(2) The color vision defect is categorized using a test such as the Farnsworth D-15, the Farnsworth 100 hue test, or the Nagel anomaloscope. If the defect is deutan in nature, the examinee goes to step 3. This document does not address the disposition of a protan defect.

(3) It should be determined whether the defect is congenital and isolated. In many cases, historical records will show color deficiency detected years beforehand. Gene sequencing, available in several university laboratories, definitively establishes the diagnosis of congenital color vision deficiency. Because acquired color vision defects are generally associated with ocular pathology [1(p. 33)], the existing NASA ophthalmological and physical examination, should rule out superimposed ocular and systemic disease. It may be worthwhile to add tritan color testing to screen for acquired color vision defects. If the color vision defect is congenital and isolated, the examinee proceeds to step 4.

(4) The examinee is judged to have adequate color vision. If accepted as a mission specialist candidate, the examinee should undergo training concerning the limitations of his or her color perception abilities and training in the use of associated personal equipment, if any.

Appendix A

NASA Man-Systems Standards for Color

Note that references [56] and [5] have the same paragraph numbering scheme internally. So, in this Appendix, a reference to a paragraph number alone, e.g. [§5.4.3], refers to the specified paragraph in both documents.

A.1 Computer Operations

NASA's rule for use of color in computers is simple and clear: "As a symbolic code, color shall be redundant with at least one other coding technique" [§9.6.2.6.2.c.1].

This requirement is not surprising. With most types of laptop computers, viewing the screen even a little off-center can drastically change the appearance of colors.

A.2 Location Coding

"Location coding" defines locations throughout the spacecraft, including control panels, display panels, stowage areas, lockers, access panels, systems, components, and equipment [5(§8.5.1)]. Color *may* be used as part of the coding scheme [5(§8.5.3.3.a)], but it is *required* that "an alphanumeric coding system shall be established for the space module" [§8.5.3.1].

Color "may be useful in helping the crewmember to more quickly identify the room type or their orientation in the rooms. Lighter colors may be used as a cue to indicate designed [sic] for a local vertical" [5(§8.12.2.2.a.6)]. Changes in texture may also be used in subdividing the interior space

[5(§8.12.2.2.b.4)]. Clearly, the color weak astronaut will not have any difficulties with location coding.

Finally, color would also be redundant if used to meet the requirement that "stowage locations and items shall be coded to allow for location, replacement, or inventory of items" [§10.12.3.c]. The location would be the primary cue.

Location coding is also mentioned in [§9.5.3.1.7].

A.3 Controls (general)

"Controls" include knobs, thumbwheels, levers, toggle switches, pushbuttons, cranks, pedals, etc. NASA identifies 17 different types of controls [5(§9.3.2.1)]. Only two types of control, pushbuttons and "legend switches," may be illuminated (discussed later). For controls in general, the following coding issues may pertain:

a) The color and size of controls will be standardized [§9.3.3.1.a.4]. In fact, "controls shall be black or grey unless special functions dictate otherwise (e.g., emergency evacuation controls are striped black and yellow)" [5(§9.2.2.2.4.c.1)].

b) Emergency or critical controls will be coded or labeled [§9.3.3.1.h/i].

c) "If several functional groupings of displays and controls are placed in close proximity on a control panel, an effective means of discriminating between them shall be provided (e.g., color coding or outlining)" [5(§9.2.3.2.3.d and §9.5.3.1.12.a)].

In none of these cases is color a nonredundant cue. The control's location and its label are the primary cues. Any quantifiable effect on efficiency and speed due to color is likely to be dwarfed by inter-individual variations in skill, training intensity, and motivation.

A.4 Controls (specific)

References [56] and [5] mention color in the context of specific types of controls:

a) Thumbwheel – "Thumbwheel controls shall be coded by location, labeling, or color (e.g., reversing the colors of the least significant digit wheel as on typical odometers)" [5(§9.3.3.3.2.c.1)].

b) Levers – “When several levers are grouped in proximity to each other, the lever handles shall be coded” [§9.3.3.3.6.a]. Color, if used to code such levers, would be redundant. Each lever’s position and label would be the primary cues.

c) Legend switches - “The legend shall be visible with or without internal illumination” [5(§9.3.3.3.15.c.2)].

d) Pushbuttons – There are 4 types of pushbuttons. Pushbuttons may include “signal lights,” but it is not explicitly explained what function these lights serve [5(§9.3.3.3.8)]. The only way in which pushbuttons could confuse a color weak astronaut is if the button’s state of activation was indicated by the color of the signal light. This is unlikely: NASA discourages the use of lighted pushbuttons, and this would represent an even more complicated lighted push button. Lighted pushbuttons are discouraged because:

    (i) They cause a continuous power drain [5(fig. 9.3.2.1-1)].
    (ii) Bulb failure can lead to erroneous interpretation of status [5(fig. 9.3.2.1-1)].

e) Circuit breakers – “Except for special cases, circuit breakers shall be of the plunger type (pull-to-release, push-to-reset). ... The tripped condition of the plunger-type circuit breaker shall be indicated by a white or silver band. When the circuit breaker is closed the band shall not be visible” [5(§9.3.3.3.13)]. The only other type of circuit breaker mentioned is the “switch-type” circuit breaker, which uses the position of the handle to indicate the tripped state [5(§9.3.3.3.13.d.2)]. On the space station, only the plunger type of circuit breaker will be used [56(§9.3.3.3.13.a.3)]

A.5 Caution and Warning System

There are three classes of cautions and warnings: (1) Emergency, (2) Warning, (3) Caution. Although color is used in the visual annuncuation of these conditions, all of them also include an auditory signal, which [56] and [5] spell out in great detail:

- a siren sounds for a smoke/fire emergency,
- a klaxon sounds for a rapid change in cabin pressure,

- an alarm tone (sine wave) sounds for a toxic atmosphere emergency,
- a square wave sounds for a warning situation,
- a "general tone" (different from the others) sounds for cautions.

Color is unquestionably redundant and secondary: The auditory channel must be primary so that emergency notifications can be delivered even when all crewmembers are asleep [§9.4.4.3.1 and subparts].

A.6 Displays

NASA recognizes 9 types of displays [5(§9.4.2.3.3.2-10)]. We will discuss only those in which color participates.

a) Dials, scales, and pointers – "When certain operating conditions always fall within a given range on the scale, theses areas shall be made readily identifiable by means of pattern or color coding applied to the face of the instrument" [§9.4.2.3.3.4.f] Color is redundant because the absolute position of the pointer is the primary cue. The Australian court system also made the judgement that color weak aviators are not handicapped by this type of display [2(§70)].

b) Flag displays – "Alphanumeric legends shall be used in lieu of, or in addition to, color coding whenever possible" [5(§9.4.2.3.3.6.h)]. The Space Station requirement is more strict: "Alphanumeric legends shall be used" [56(§9.4.2.3.3.6.h)]. Color is redundant for all flag displays, however, because "a minimum of 75% luminance contrast shall be provided between flags and their backgrounds" [§9.4.2.3.3.6.d].

c) LEDs – Color coding may be used [§9.4.2.3.3.8].

A.7 Cables and Connectors

"Cables containing individually insulated conductors with a common sheath shall be coded" [§11.14.3.e]. The examples in reference [5] show that these codes are alphanumeric [5(figs. 11.14.4-1 & 2)], which is the only reasonable alternative, given that "connecting cables shall be marked with nomenclature or code describing the connecting cable's interface end points" [§9.5.3.1.6.e].

Although reference [5] specifically mentions cables containing multiple individual wires, nowehere does it mention simple single-conductor wires.

Given the trend toward solid-state circuitry and compenent assemblies, it is unclear whether such wires exist aboard NASA space vehicles or how common they are. It is also unclear whether color coding is used on them or not. If they use color coding, it is unknown whether they conform to [5(§9.5.3.1.5)]. We make the conservative assumption that such wires do exist and that they do use color coding.

Alignment marks – Although color coding may be used [5(§9.5.3.1.5.c)], it is required that "arrows and/or labels shall be used to indicate the proper orientation" [5(§9.5.3.1.5.b)].

Connectors – "Both halves of mating connectors shall display a code or identifier unique to that connection" [§11.10.3.5.e.1]. Given the vast number of connectors on a spacecraft and the aforementioned 9-color limit, it is unlikely that color coding is commonly used in this setting. Indeed, "discrete nomenclature of alphanumeric coding is preferred to color coding" [5(§11.10.4.a)].

A.8 Miscellaneous

The following allusions to color in reference [5] are included only for completeness. In each of these situations, a color weak astronaut has no disadvatage because color is not being used for coding:

a) Handholds and handrails – "The color of all handholds/handrails shall be standardized within the space vehicle" [§11.8.2.2.2].

b) Keyboards – "For standard keys [on all computer keyboards], the primary color shall be neutral, e.g., beige or gray, rather than a color that has a high reflectance like white" [§9.3.3.4.1.2.l.2].

c) Foot restraints – "Color for all foot restraints of a given type shall have a contrast ratio of approximately 10:1 or greater with the background" [5(§11.7.2.3.2.4.b)].

d) Equipment restraints – "Equipment restraints shall be of a standardized color to distinguish them from other types of loose equipment or items that will be retrained" [5(§11.7.3.3.i)].

e) In some cases printed materials may be color coded [§9.5.3.1.10, §9.5.3.1.13, §9.5.3.2.i.6]. Color is obviously redundant because of the lettering.

Appendix B

Color perception in transportation

All scholarly investigations of color standards in transportation will encounter the work of Barry Cole and Algis Vingrys, optometrists at the University of Melbourne, Australia. They have written extensively in support of color vision standards for the transportation industry [20, 21, 22, 81, 82, 83].

Challenges to their conclusions have appeared [60], but none in the medical literature. Fortunately, a point-by-point refutation of their conclusions is unnecessary: Cole and Vingrys were expert witnesses in the Australian court cases mentioned earlier. The court evaluated their testimony in detail and rejected every reason they cited in support of a color standard for pilots [8, 2, 7].

Two of their papers in the medical literature, however, must be addressed. The first reviews the literature dealing with color vision in transportation accidents [83]. The second deals just with driving [21]. Both papers conclude that color deficiency is a risk, opposite the conclusions of many of the authors who conducted the original studies.

Addressing these papers is important because, ideally, the only justification for restricting color weak people from jobs is hard evidence that they would jeopardize safety or efficacy. If Vingrys and Cole are unable to find real-world data demonstrating that color weak people incur such jeopardy, then most existing color standards must be rethought. As Section 5.1 of this document explains, laboratory tests are not a substitute for measures of actual field performance.

The next three subsections discuss shortcomings of the two Cole and

Vingrys papers.

B.1 Methodological Issues

Accident Reports. The most obvious way to demonstrate that defective color vision causes accidents is to analyze accident reports. Vingrys and Cole bemoan the difficulty of this approach:

> Of course, accident analyses are not a very satisfactory means for identifying risk factors. In relation to exposure, accidents are not common events... and, even when they do occur, they can be the result of a diverse range of factors or interactions between factors. [83(p. 267)].

In fact, accident analyses are the *best* means for identifying risk factors. This is why the US military aviation community devotes so much effort to accident investigations.

As section 3.5 noted, accident analyses have had no difficulty detecting the risk caused by using a cellular telephone [65] or by having a current benzodiazpeine prescription [10].

Defectives Eliminated. Vingrys and Cole next remark: "Evaluating the role that a defect of color vision has for accident causation is made all the more difficult by the imposition of colour-vision standards since the 1870s, so that only a small proportion of people taking critical responsibility in transport operations will have a defect of colour vision" [83(p. 267)].

This is obviously untrue for driving, where there are no color standards for the general population. Furthermore, section 3.5 showed that throughout the past century-and-a-quarter of institutionalized color vision testing, enormous numbers of significantly color defective men have entered into training for various transportation professions.

Whether men who enter these professions stay in them is another question and, given the stakes, difficult to study. In a consecutive series of 4801 aircrew members referred to the US Air Force School of Aerospace Medicine, of which 3509 were pilots, 25 "surprise" diagnoses of color deficiency were made [74]. Because this was a highly selected, not random, sample of the Air Force flying population, the meaning of this finding is unclear. It may be that self-selection occurs. Interestingly, the most severely color defective man in the series was a pilot with the rank of Major General and 6000 hours of flying time.

B.2 Accidents Due to Color Deficiency

B.2.1 Case Reports

The worldwide search for color-related accidents by Vingrys and Cole turned up the following:

a) A 1913 review of 20 maritime and rail accidents ascribed to vision problems. Vingrys and Cole believe only 2 of the cases involve a congenital defect of color vision and "even for these two cases there is some uncertainty."

b) An "unsubstantiated" (their description) 1929 report that 9.5% of all accidents on the French railways were due to defective color vision.

c) An 1891 report on 10 railway accidents the 19th century author felt were due to defective color vision. They discuss only two of these cases, blaming one on bad weather and another on politics.

That's all. Relevant reports may have appeared since the Vingrys and Cole paper was published in 1988, but none of their publications since 1988 suggest this has happened.

B.2.2 Statistics – Aviation accidents

Vingrys and Cole next examined compilations of data with the potential to show that color deficiency is a risk for transportation accidents.

Only two studies have examined the aviation risk of color deficiency, and only in civil airmen. Wick refers to a third [84]:

> Some years ago, two CAA (the predecessor of the FAA) researchers, Brimhall and Franzen, performed an excellent retrospective analysis of civilian aircraft accidents and were able to find no correlation at all between color vision weakness and accident rates. Unfortunately, I do not believe the study was ever published.

The other two studies are by Harper in 1964 and by Dille and Booze in 1976 and 1980. They are difficult to interpret.

The Dille and Booze study examined general aviation accidents for 1974-1976, stratifying the accident population by whether the airman had a color vision waiver. The data are problematic because the group with defective color vision flew four times as many hours as the color normal group in the six months before the accident. The appropriate denominator for comparisons is therefore, not obvious. Ultimately, Dille and Booze concluded that accidents per flying hour in the preceding six months was most appropriate measure. Using it, the difference between the color normal and color waivered groups was statistically not significant. Vingrys and Cole choose a different denominator and conclude that color vision is a risk.

Zentner sums it up best: "no research has been conducted that satisfactorily links colour vision defects causally with aviation accidents" [85].

B.2.3 Statistics – Road accidents

In 1997 Cole and Maddocks published a paper with the provocative title "Defective colour vision is a risk factor in driving" [21]. They begin by noting "there has been a long and somewhat inconclusive debate as to whether or not defective color vision is a risk factor in driving motor vehicles." The rest of the paper is embarassing to read. They properly challenge the case series that Verriest et al [79] describe as offering "definite proof that colour-defective drivers do not have more accidents than people with normal colour vision".

Then, however, Cole and Maddocks invent a new control group for the Verriest data by using an indefensible, ad hoc method. With this new control group, the odds ratio for defective color vision is 1.11 (95% confidence interval 0.95 to 1.31). Rather than admit this is not statistically significant, Cole and Maddocks make the embarassing counter-claim that "the confidence interval raises the statistical possibility that the odds ratio may be as high as 1.31."

There are few authorities, other than Cole and Vingrys, who believe that color deficiency adds risk to driving. How could we convince them that the risk, if any, is so minor as to not be worth our concern? Let us examine market forces.

In the United States, automobile insurance is a multii-billion dollar/year business, covering 176 million drivers. Although it is an extremely competitive industry, there is apparently no automobile insurance policy that gives a discount for having normal color vision or imposes a surcharge for having deficient color vision. The absence of such practices cannot be ascribed to an absence of data: hundreds of thousands of professional drivers have been involved in non-fatal vehicular crashes and afterwards subjected to detailed medical examination. Whether or not the insurance industry actually collected data on color perception is immaterial – the opportunity was certainly there.

By contrast, many insurance companies will immediately and substantially increase a driver's premium after a single speeding ticket is charged to the driver. It is fashionable nowadays to let market forces drive what were once regarded as policy decisions. The insurance industry's market forces have clearly made a judgement: a history of a speeding ticket incurs a higher risk than does defective color vision.

B.3 Syndromes of dyschromatopsia

We believe it is important to fully analyze the data relating road accident data to color vision deficiency. Road travel has the advantage of an enormous "n" – millions of color defective men engage in it every day. It has also the characteristic of being dependent on split-second decision making.

We believe that the lack of clear evidence associating color weakness with driving accidents is a strong statement supporting no overall increase in risk. The reason is: every retrospective study of driving and color vision conducted to date overestimates the prevalence of congenital color deficiency because they do not exclude acquired defects of color vision.

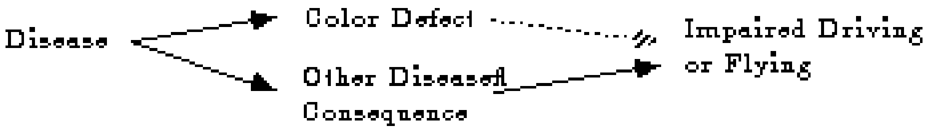

Figure B-1. Dyschromatopsia syndromes complicate the assignment of cause and effect in accidents. The striped arrow represents an incorrect causal influence that will be drawn unless the other cause is recognized.

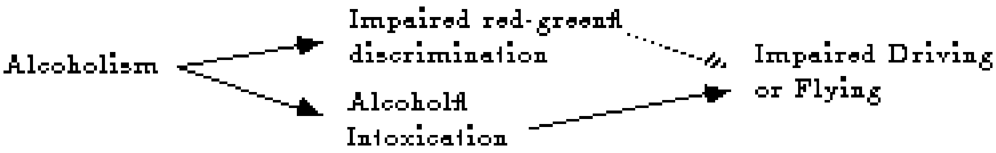

Figure B-2. Alcoholism leads to an excessive indictment of color vision as a cause of driving or flying accidents.

Figure 1 postulates a disease that is associated with color perception defects and with other defects known to impair driving ability. We will examine alcoholism as an example.

We all know that alcohol intoxication, part of the alcoholism syndrome, impairs driving. Another part of the syndrome includes impaired color perception. Persons consuming large amounts of alcohol, especially in combination with tobacco, have impaired red-green discrimination abilities. For example, although he was vague about the source of patients, Pinckers found a red-green defect in 43 of 66 eyes belonging to subjects "suspected of intoxication or being on treatment" [64].

Alcoholics will, of course, be over-represented among a population of accident victims because of alcohol's intoxicating effects. But, alcoholism's accompanying color defect will also be over-represented.

To explain figure 1 in other words, alcoholism may be directly responsible for the accident through intoxication, but color vision testing will implicate color deficiency unless care is taken to detect the underlying disease.

This situation could be quite common. The table below identifies syndromes of red-green color deficiency that could impair driving ability through non-color mechanisms. The table is long and not complete. It includes some extraordinarily common diseases.

Disease	**Color Defect**	**Other Consequences**	**Refs**
alcoholism	red-green	impaired cognition	[64]
diabetes	tritan (early), deutan (later)	(1) impaired cognition, due to hypoglycemia or ketosis (2) diabetic eye disease	[14]
heart failure	pseudo-protanomaly from digoxin therapy	impaired cognition, due to cerebral hypoperfusion, e.g. pump failure or arrhythmia	[9]
atrial fibrillation	pseudo-protanomaly from digoxin therapy	as above	[9]
depression	red/green impairment from MAO-inhibitor therapy	(1) slow reaction times (2) suicide attempts	[38]
glaucoma	(1) tritan and red-green (2) blue-green insensitivity due to acetazolamide therapy	(1) visual field limitation (2) contrast insensitivity	[49]
multiple sclerosis	red-green due to optic neuritis	cognitive and neurologic impairment	[1]
Parkinson disease	tritan and red-green defects	impaired muscular control	[16]

Ocular side effects of drugs often impair color vision before other visual functions. According to Koellner's rule, retinal damage usually leads to a tritan defect and pseudo protanomaly, whereas damage to the optic nerve, ganglion cell layers, or visual pathways weakens red/green discrimination [1(p. 32), 38].

In summary, any cross-sectional retrospective study of accident rates should look for fellow-travelers of abnormal color vision. No study yet performed has done this, which means that even the neutral results obtained in examining the risk of driving while color blind are evidence against an effect.

B.4 Summary

Our critical examination of Cole and Vingrys' work discloses two major findings:

a) Despite almost a century of uninterrupted, inadequate color vision screening, there appears to have been exactly one transportation accident (a near miss) ascribed to defective color vision since 1907.

b) Split-second control of automobiles is successfully done by millions of color weak men every day. Multiple studies have failed to ascribe a risk to defective color vision, despite the fact that a hitherto-undescribed methodological flaw slants every such study toward risk.

Appendix C

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