THE PUZZLE OF THE CRASH OF FEDEX FLIGHT 1478: IMPLICATIONS FOR COLOUR VISION STANDARDS IN AVIATION

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ABSTRACT

During the final approach to land on Runway 9 at Tallahassee Regional Airport, Federal Express (FedEx) Flight 1478 crashed into a forest about a mile short of the Runway 9 threshold. The Precision Approach Path Indicator (PAPI) device servicing the runway was supposedly showing four red lights during this final approach, providing colour-coded information that the approach was too low for a safe landing. The First Officer, piloting Flight 1478, had a colour vision defect, and the crash has raised the question of whether colour vision standards in aviation should be more stringent than they currently are. In this paper, we argue that the crash of FedEx Flight 1478 raises the more fundamental question of whether colour-coded information should be used at all in aviation. The basis of our argument is this puzzle: While the First Officer, piloting, had defective colour vision, the Captain and the Flight Engineer, both actively involved in the approach to land of Flight 1478, had normal colour vision, yet did not seem to see, and certainly did not make use of, the colour-coded information supposedly provided by the PAPI device. We describe how the National Transportation Safety Board's (NTSB) Report implicitly acknowledges and attempts to explain this puzzle. We propose an alternative explanation of this puzzle, and conclude by considering the implications of this alternative explanation for colour vision standards in aviation.

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INTRODUCTION

On July 26, 2002, in pre-dawn darkness, FedEx Flight 1478 crashed into a state forest about a mile short of the threshold of Runway 9 at Tallahassee Airport in Florida, USA. The reconstructed flight profile of Flight 1478 (the blue line in Figure 1) is typical of a 'black hole' accident. These accidents involve pilots' misperception of their glideslope angle to a runway as higher than it actually is (see Gibb, Gray, & Scharff[1] for a comprehensive discussion of this topic). Because of this misperception, pilots descend too steeply and often impact the ground short of the runway, in what constitutes an 'undershoot accident'. The NTSB Report[2] into the crash indicates that Runway 9 at Tallahassee had a classification of moderate risk of 'black hole' accidents. However, the visual approach to Runway 9 was equipped with a precision approach path indicator (PAPI) device, the primary purpose of which is to prevent 'black hole' accidents by providing pilots with information about their glideslope angle during approach to landing.

THE PAPI

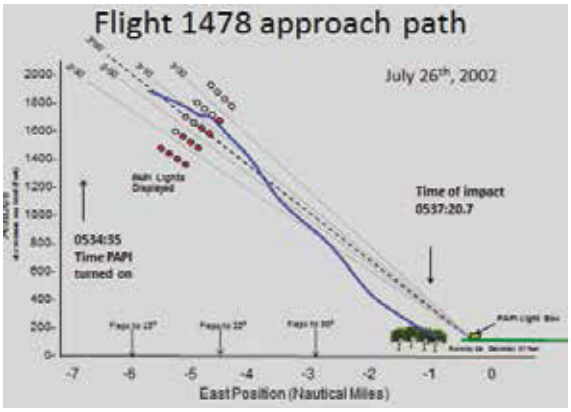
PAPI devices use four light beams, each 'split' into an upper beam of white light, and a lower beam of red light. The colour of each of the four PAPI lights visible to an approaching observer depends on the elevation of the observer above ground level. This elevation is different for each of the four lights. This results in five separate colour-coded patterns of the PAPI lights, each pattern signalling different information to pilots about their angle of approach: A pattern of four white lights signals that the approach is too high; a pattern of three white and one red lights signal the approach is a little high; a pattern of two white and two red lights signals the approach is at 3°, appropriate for a safe landing; a pattern of one white and three red lights signal the approach is a little low; and a pattern of four red lights signals the approach is too low for a safe landing.

The five vertical wedge-shaped sectors of airspace in which these five colour-coded patterns of PAPI lights are theoretically visible are shown in Figure 1, with the apex of each wedge-shaped sector at the location of the Runway 9 PAPI device. Overlaid on these five sectors of airspace is the vertical flight profile of FedEx Flight 1478 during final approach. Figure 1 therefore shows the different patterns of PAPI lights supposedly visible to the crew of Flight 1478 during its approach to land.

In theory, observation of a pattern of four white PAPI lights by a pilot and crew of an aircraft should result in lowering the nose of the aircraft to steepen the descent in order to intercept the 'proper' approach angle of 3°. Similarly, observation of a pattern of four red PAPI lights should result in the pilot and crew aborting the approach, and initiating a 'go round'. It is clear from the flight profile shown in Figure 1 that although during the final three minutes of Flight 1478, a pattern of four red PAPI lights was supposedly visible to the crew, their actions were more consistent with perception of a pattern of four white PAPI lights ('lower the nose of the aircraft') than perception of four red PAPI lights ('go round').

Figure 1.

The blue line shows the reconstructed flight profile of Flight 1478 over about the final six nautical miles and about final three minutes before it crashed into trees short of Runway 9. Also shown are the five wedge-shaped sectors of vertical airspace radiating from the Runway 9 PAPI device, and the different patterns of white and red PAPI lights supposedly visible in each sector, corresponding with the final approach of Flight 1478. The distances to run at which the various stages of flaps were set are shown on the horizontal axis. (Adapted from NTSB[2]).



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NTSB REPORT

The NTSB Report of the post-crash investigation noted that two of the three crew in the cockpit of Flight 1478, the Captain and Flight Engineer, had normal colour vision. However, the First Officer, piloting, had defective colour vision diagnosed as severe deuteranomaly[1], the most common sub-type of congenital 'red-green' colour vision defects. These colour vision defects are manifested in observers as difficulty in discriminating between, and correctly naming, a variety of coloured light sources. The NTSB Report added that a person diagnosed with deuteranomaly could have significant difficulty in discriminating between red and white light sources, such as those used in PAPI.

Given these facts, the statement in the NTSB Report that the colour vision defect of the First Officer was a contributing causal factor in the crash of Flight 1478, seems, at first glance, a reasonable conclusion. And, if this conclusion is accepted, recommendations to the United States Federal Aviation Administration (FAA) in the NTSB Report that colour vision test protocols be made more effective in screening out pilot applicants with colour vision deficiencies that could impair their ability to perform colour–related critical aviation tasks, including (but not limited to) correct interpretation of glideslope information and in-cockpit displays that use colour to convey information, also seem reasonable. Furthermore, given the above, it is not surprising that in the nine years since the Report was published, the crash of FedEx Flight 1478 has been cited in conference presentations[3], journal articles and monographs[4], aviation medical textbooks[5] and the ICAO Manual of Civil Aviation Medicine[6] as providing evidence of the need for more stringent colour vision screening protocols in aviation. However, the seemingly reasonable conclusion in the NTSB Report about the causal role of the First Officer's colour vision defect in the crash of Flight 1478, and the seemingly reasonable consequential calls for even more stringent colour vision standards in aviation, are brought into question by a puzzle raised by the crash.

The puzzle raised by the crash of Flight 1478 can be expressed simply in the form of a question that follows four assumptions stated as facts in the NTSB Report as follows:

Assumption/Fact 1: All three crew (Captain, First Officer, Flight Engineer) were actively engaged in the approach to land.

Assumption/Fact 2: The Runway 9 PAPI device was providing veridical colour-coded information to the crew as to the dangerously low approach angle being flown (viz., four red PAPI lights; see Figure 1).

Assumption/Fact 3: This colour-coded PAPI information was denied to the First Officer, piloting, because of his defective colour vision.

Assumption/Fact 4: However, this colour-coded information was available to Captain and the Flight Engineer, because of their normal colour vision.

Question: Why did the Captain and the Flight Engineer, both with normal colour vision, not make use of the colour-coded PAPI information to prevent the accident?

The NTSB Report seems to suggest some awareness of this puzzle, and an attempt to explain it. Consider the paragraph headed "3.2 Probable cause" on page 68 of the NTSB Report, in which four factors are identified as "contributing" to the crash of Flight 1478. Part of this paragraph reads:

> "Contributing to the accident was a combination of the Captain's and First Officer's fatigue, the Captain's and First Officer's failure to adhere to company flight procedures, the Captain's and Flight Engineer's failure to monitor the approach, and the First Officer's color vision deficiency."

Some awareness of what we have termed the puzzle is reflected in the third of the four "contributing" causes listed, namely "the Captain's and Flight Engineer's [both with normal colour vision] failure to monitor the approach"; that is, failure to ensure the pilot made use of the colour-coded information being provided by the Runway 9 PAPI device. A two-factor explanation of the puzzle appears to be identified in the Report. The first factor is the "fatigue and failure to adhere to company flight procedures" on the part of the Captain, and the second factor is the "(possible) fatigue" and "(possible) work overload" on the part of the Flight Engineer (see paragraph 11 on page 68 of the NTSB Report).

In summary, the NTSB Report can be interpreted as saying that because of these two factors, the two crew with normal colour vision did not make use of the colour-coded PAPI information *available* to them, but *unavailable* to the First Officer (because of his defective colour vision, and exacerbated by fatigue), and consequently they did not intervene to correct the unsafe approach path being flown.

The behaviour of the crew during the final approach suggests an alternative explanation of the puzzle of the crash of Flight 1478. Given the conversation between the three crew (e.g., selecting 'gear down', and the setting of the progressive stages of flaps within the three minutes before impact), it is clear that all crew were actively involved in the concluding stages of Flight 1478, beginning with the decision to change the landing runway from Runway 27 to Runway 9. On this basis, it seems implausible that the crew did not look at Runway 9 and its PAPI device during the final approach. Further evidence for this implausibility is provided by the 'paired' actions of the First Officer (who had control of the thrust and primary flight control settings), and the Captain (who manipulated the controls for settings of the flaps at appropriate stages of the approach). Inspection of the reconstructed flight profile in Figure 1 shows that these settings were appropriate for an approach that was too high, and the transcript of the cockpit conversations between the crew shows that there was no concern expressed about these settings, the conversation being consistent with an expectation of a safe landing. Given the likelihood that the crew were looking at Runway 9 and its PAPI device during the final approach, the actions of the crew and their cockpit conversation are not consistent with their seeing a pattern of four red PAPI lights, signalling a dangerous and unsafe approach to land. This raises the question: What did the crew actually see when looking at the PAPI device?

AN ALTERNATIVE EXPLANATION OF THE PUZZLE

As already noted, the actions of the crew of Flight 1478 as reflected in Figure 1 in the reconstructed flight profile of the final stages of Flight 1478 are *not consistent with* the crew seeing four red PAPI lights[1]. However, these actions *are* consistent with the crew seeing four *white* PAPI lights. This begs the question: 'Can red PAPI lights look like, and therefore be confused with, white PAPI lights, and if so, under what conditions?' Two different answers to this question seem to be provided in the NTSB Report, and can be summarised as follows:

Answer 1: 'No, red PAPI lights cannot look like, and therefore be confused with, white PAPI lights. However, if aircrew are fatigued, and fail to follow procedures, they may not see PAPI lights at all.'

Answer 2: 'Yes, red PAPI lights can look like, and therefore be confused with,

[1] *In the record of interview of the Captain two days after the crash, he reported that at no stage of the approach did he see four red PAPI lights, describing what he saw as "pink-white" at the time that 30 degrees of flaps were set.*[6]

white PAPI lights. This confusion can occur when aircrew have defective colour vision, are fatigued, and fail to adhere to procedures.'

However, there is another answer to this question:

Alternative answer: 'Yes, red PAPI lights can be confused with white PAPI lights under particular conditions which can be categorised as ***operational and atmospheric.'***

'Operational conditions' relate to the actual functioning of PAPI devices, whereas 'atmospheric conditions' relate to the conditions in the air between the PAPI devices and the aircrew observing these devices.

Before discussing these operational and atmospheric conditions, it is appropriate to elaborate in simple and direct terms our alternative explanation of the puzzle of the crash of Flight 1478 inherent in the alternative answer above. This alternative explanation is that in the final minutes before the crash of Flight 1478, operational conditions related to the Runway 9 PAPI device, and atmospheric conditions present in the vicinity of Runway 9 were such that the four PAPI lights appeared pinkish-whitish rather than red. That is, the PAPI device appeared to be signalling that the approach of Flight 1478 was too high for a safe landing, necessitating a steeper approach to land. As a consequence of this steeper approach, Flight 1478 crashed short of Runway 9.

Support for this alternative explanation is provided by Clark and Gordon[8] in the report of their investigation of PAPI devices. Clark and Gordon identified two operational conditions and one atmospheric condition that can result in confusion between red lights and white lights, which are of direct relevance to the crash of Flight 1478:

Operational condition 1: Operating temperature of PAPI lights. As the temperature of an incandescent white light source is lowered, for example when the light source is dimmed, changes occur in both the intensity and the spectral composition of the light produced. Consequently the light source appears less bright, and its colour appearance appears to change from white to yellow-orange. The lights of the PAPI device on Runway 9 were dimmed for night-time operation compared to day light operation, the default night time brightness level for both the PAPI device and runway lights being set at 20% of maximum day light brightness. As noted by Clark and Gordon, in such 'dimmed' operational conditions a white light source may appear yellow-orange rather than white.

Operational condition 2: Contamination of PAPI device components. Clark and Gordon described the role of contamination of PAPI device components (e.g., the surface of the light source, surfaces of the lenses and of the filters) on the appearance of PAPI lights. The presence of contaminating matter (e.g. dust, grime, dew, etc.) on these surfaces causes scattering of light passing through, or reflected by, these surfaces. Such scattering can result in what Clark and Gordon term "cross talk" between the white and red PAPI light beams producing both a desaturation of red light (loss of intensity of colour appearance; red light appearing pink), and also a change in its hue (actual colour appearance; red light appearing orange; the Abney effect, see Walraven[9]).

At the time of the crash of Flight 1478, the ground level temperature and dew point were both at 23° Celsius, a meteorological concurrence that was highly likely to lead to formation of dew on the surfaces of the components of the Runway 9 PAPI device. According to the NTSB Report, the Runway 9 PAPI device and white runway lights were triggered by the Captain of Flight 1478 less than three minutes before the crash. Furthermore, within four months of the crash of Flight 1478 crash the United States FAA[10] circulated an advisory warning that PAPI devices should be operated continuously to allow the heat generated by the PAPI light sources to prevent the formation of dew on surfaces of PAPI components. The FAA advisory warning was based on a report from Transport Canada that had been originally provided to the FAA in 1985, warning of the likelihood that contamination by dew could produce errors in the colour appearance of PAPI lights. This warning is consistent with Clark and Gordon's findings. With the wisdom of hindsight, this FAA advisory warning makes clear that the switching on of the Runway 9 PAPI and runway lights for such a brief time (less than three minutes before landing was due to occur) was potentially problematic under the prevailing meteorological conditions confronted by the crew of Flight 1478.

The atmospheric condition discussed by Clark and Gordon also involves scattering of light caused by contamination, except that the scattering is caused by particles (e.g., water droplets, dust, smoke, smog) suspended in the air separating a light source and an observer. Such atmospheric scattering produces similar changes in the appearance of white and red lights as described above. The NTSB Report noted that at the time of the crash of Flight 1478 two thin layers of stratus cloud were present at 25 feet and 60 feet above ground level in the vicinity of the Tallahassee Airport. We agree with the NTSB Report that the presence of this cloud was unlikely to be a causal factor in the crash in terms of the disruption to visibility of Runway 9 due to the cloud. However, it is plausible to suggest that the presence of cloud did contribute, in addition to the conditions discussed above, to change the appearance of the colour of the Runway 9 PAPI lights consistent with the findings described by Clark and Gordon in their report.

In discussing the implications of their investigations, Clark and Gordon introduce the concept of *fail unsafe* in relation to the operation of PAPI devices, a concept best understood when contrasted with the concept of *fail safe*. Devices or systems designed to *fail safe* are designed such that when they fail to operate properly, any dangerous consequences of such failure are eliminated or at least minimised. For example, the so-called 'dead man's switch' incorporated in the operation of some machines requires an operator to actively engage a switch in order for the machine to function. If the switch is disengaged (e.g., the operator is incapacitated), the machinery automatically ceases to function, thereby rendering it safe while its operator is so incapacitated. Contrary to this situation, Clark and Gordon make the point that when PAPI devices fail, for example in the conditions discussed above, PAPI lights signalling 'too low' (i.e., four red lights) may be interpreted as signalling 'too high' (i.e., four white lights) resulting in unsafe actions on the part of observers making this interpretation. It needs to be stressed that Clark and Gordon's warning about this ***fail unsafe*** nature of PAPI devices applies to all observers, and not only to those with defective colour vision. On the flight deck of Flight 1478 as it approached to land on Runway 9 were three crew, one with defective colour vision and two with normal colour vision. Their actions and the consequent crash were consistent with Clark and Gordon's warning about the ***fail unsafe*** nature of PAPI devices.

Fundamental to Clark and Gordon's concept of ***failing unsafe*** in their discussion of PAPI devices is the ease with which the colour appearance of a light source or an object can be distorted by various viewing conditions. More importantly, such distortions of colour perception can occur with observers with normal colour vision. While the viewing conditions discussed by Clark and Gordon may be difficult, if not impossible, to be experienced by readers of this paper, readers can readily experience distortions of colour perception in normal viewing conditions by looking at what are termed ***colour illusions.*** Many striking examples of such colour illusions are available at various web sites. The links to three such sites are provided below:

http://www.michaelbach.de/ot/
http://www.echalk.co.uk/amusements/OpticalIllusions/illusions.html
http://www.psy.ritsumei.ac.jp/~akitaoka/90901500585.pdf

Given the unreliable nature of colour perception discussed by Clark and Gordon in reference to PAPI devices, and demonstrated in the many colour illusions shown at the web sites cited above, it seems self-evident that the use of colour as a medium for information coding as occurs in PAPI devices is inherently problematic. This point was made by Walraven[9] in his review of various misperceptions of colour that should be considered when designing colour-coded visual information presentation displays. He concluded (p. 41):

> "The various phenomena we have discussed warn against the use of colour as a fully predictable medium for encoding information. We may be able to define precisely a colour in the physical sense, but the perceptual response to that colour depends on the viewing conditions and other visual stimuli in the field of view."

CONCLUSION

The exclusion of pilots with defective colour vision from the aviation industry is described by Pape and Crassini[11] as depending on three assumptions which underlie the application of colour vision standards in aviation.

> ***Assumption 1:*** Some information necessary for the safe piloting of aircraft is presented to pilots in a solely colour-coded form.
>
> ***Assumption 2:*** Pilots with defective colour vision will make errors in processing such colour-coded information, and consequently will pilot aircraft unsafely.
>
> ***Assumption 3:*** Pilots with normal colour vision will not make errors in processing such colour-coded information, and therefore will operate aircraft safely. This is a corollary of Assumption 2.

In these concluding comments we briefly discuss the validity of first and third of these assumptions, and note the implications of this discussion for the validity of the second assumption.

Assumption 1: In almost all cases, information is provided to pilots in the aviation environment in a redundant form. For example, the same warning may be presented in the cockpit in an auditory form (this may vary between aircraft types), and in a visual form (the pilot sees a flashing warning light illuminated, or the word 'Warning' flashing on a display, and the colour and/or brightness and/or rate of flashing of the warning light/text changes with the degree of danger being signalled). In the CAA UK report[12] of a detailed task analysis of the role of colour in the cockpit displays of the Airbus A321 and Boeing 757, and in the aviation environment in which aircrew of these commercial aircraft operate, it was concluded that the most colour critical elements in the pilots' environment were PAPI lights and the terminal parking guidance lights. However, even with PAPI displays, the information is presented to pilots redundantly. The white light and red light beams in PAPI devices are not equiluminant; that is, white and red PAPI lights do not appear equally bright. As pointed out by Clark and Gordon, this means that PAPI devices involve both a colour-spatial code and a brightness-spatial code in presenting information. For example, the PAPI device signal for optimal approach angle can be described as follows: Four lights; two white (brighter) lights on the right, two red (dimmer) lights on the left.

Assumption 3: The third assumption rests on the proposition that observers with normal colour vision always perceive colours veridically. The problematic nature of this proposition is self-evident in the distortions of colour perception that can be experienced in the colour illusions provided at the web sites cited above. More formal evidence of the problematic nature of Assumption 3 is provided by Walraven, and in the work of Clark and Gordon, which formed the basis of our alternative explanation of the puzzle of the crash of Flight 1478.

Assumption 2: What are the implications of this discussion of Assumptions 1 and 3 for Assumption 2? We argue that on the basis of the material we have presented, the validity of both Assumption 1 and Assumption 2 can be questioned. Redundancy in information coding in aviation occurs almost universally, even in PAPI devices. Misperceptions of colour appearance occur commonly with observers with normal colour vision. It follows that excluding from the aviation industry those pilots who may have difficulty in processing one of these redundant codes, namely colour, does not seem warranted, certainly not on the basis of the crash of Flight 1478. We end by stressing that our conclusion should not be interpreted as a denial of the existence of defective colour vision. Our point is captured nicely by the puzzle of Flight 1478: Three aircrew were in the cockpit, two with normal colour vision, yet the colour-coded information supposedly provided by the Runway 9 PAPI device was not used to ensure a safe landing.

Editorial note.

Althoug This article raises some very interesting questions related to the prominent use of colour cues in aviation. Although the authors argue against the exclusion of pilots with defective colour perception from the aviation industry, the foundations of their argument could also be applied to so-called 'colour normals'. There are a number of retinal pathologies and medications that are associated with acquired colour deficiencies, including amongst pilots. In fact, distortion of colour is often one of the early indicators of underlying retinal disease. (Add to this the possibility that some pilots with colour confusion may have been incorrectly classified as 'colour normals' at the time of their initial medical). Despite the possibility of acquired colour deficiency in trained aircrew, there is no requirement for aircrew to have colour vision screening at regular intervals during their career. If the industry holds that colour is such an important cue for flight safety, should there be a requirement for applicants to demonstrate 'normal colour vision' as part of the medical recertification process?

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