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HEALTH & SAFETY LABORATORY

Dark Adaptation and Lookout Duties

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CONTENTS

EXECUTIVE SUMMARY

OBJECTIVES

This research project aims to clarify and quantify the demands of the working environment and watch-keeping regime for large commercial ships in relation to dark adaptation and other factors that can influence the performance of a night time Lookout such as age, health, working routine and safe manning hours. The objectives of this research were to:

- Based upon STCW Section A-VIII/2 part 3, and in particular part 3-1, conduct a task analysis of night time lookout duties, to identify the demands in relation to dark adaptation and levels of night-vision, in the environment of the bridge of a merchant ship.

- Consider the relevant available evidence on visual performance in relation to dark adaptation and other aspects of night time vision.

- Prepare a report summarising the findings of the task analysis and the relevant existing evidence on visual performance and any additional observations relevant to dark adaptation from the work undertaken and, where relevant, make recommendations in relation to best practice for bridge management and safe operating procedures for night time bridge lookout duties at sea.

METHODS

This study comprised:

- A literature review to identify peer-reviewed studies on visual performance in relation to dark adaptation and other aspects of night time vision such as scattering of light and changes to the pupil size due to ageing.

- Ship visits to two roll-on, roll-off and passenger ferries (RoPax) and to an oil tanker to observe the activities associated with maintaining a safe navigational watch at night. Observation of different ship types ensured that any differences in practice of night time lookout duties were captured.

- The collection of data from these visits included: Measures of luminance and illuminance of equipment and the environment within the operator’s field of view on the bridge, the unobtrusive infrared videotaping of the bridge team undertaking their duties at night, and informal, unstructured interviews with members of the bridge team.

MAIN FINDINGS

With respect to Dark Adaptation:

- On moving from an environment with higher ambient light levels to one with lower levels, the sensitivity of the eye changes (increases), and the time taken to reach the new steady-state of sensitivity will depend upon the difference in light level.

- The processes of dark adaptation, and its effects on visual performance have been investigated in detail previously under laboratory conditions, but there are no studies relating specifically to modern merchant ship bridge conditions, and no experimental data that can be easily applied in the current context.

- Under laboratory conditions, very bright pre-adapting lights are used, and it can take up to 40 minutes for the eye to adapt to complete darkness. However, it is highly unlikely that the bridge crew will, prior to commencing night time lookout duties, be exposed to comparably bright pre-adapting lights.

- Lighting levels on the bridge are such that only partial dark adaptation occurs. As a consequence, the Lookout’s eyes would never become fully dark adapted, and it would therefore take less time after entering the bridge for the eyes to reach their steady state of adaptation.

- Adaptation to lighting conditions on the bridge will normally be achieved in 15 minutes, but there are a range of personal factors that can influence this.

With respect to individual characteristics:

- There are a range of individual differences that influence the rate of adaptation and the threshold sensitivity achieved. For example, dark adaptation has been shown to slow with increasing age.

- The tests currently used to routinely assess seafarer’s vision are poor predictors of performance under night time conditions on a ship’s bridge.

With respect to the bridge environment:

- The watch handover periods observed were shorter than the timescales recommended in both IMO MSC.1/Circ.1280 and the bridge procedures guide.

- Light levels on the bridge were well within the recommended standards.

- Light levels in the chartroom of the ships visited were higher than the recommended maximum levels.

- The navigational watch involves large periods of time where nothing noteworthy happens, and both the Officer of the Watch and the Lookout are only required to perform routine tasks. This can create excessively low workload (underload), which can affect performance.

- Vigilance may be as important as dark adaptation in the detection of dim lights at night. There is a negative impact on vigilance during prolonged exposure to a task, which can be exacerbated if the task is particularly monotonous.

- Night time Lookouts are trying to maintain performance efficiency during the worst time of day for doing so. Vigilance tends to decrease periodically at least twice during 24 hours, typically between 13:00 and 16:00 and 01:00 and 06:00.

With respect to the external environment:

- The intensity and position of navigation lights on larger vessels is such that the sensitivity of the eye under normal ambient bridge illumination conditions is likely to be sufficient for their visibility to be acceptable. This may not be the case for poorly lit small craft.

POINTS FOR FURTHER CONSIDERATION

The following points for further consideration are raised as they may protect, improve or maintain the operational night vision of seafarers:

With respect to Dark Adaptation:

- As current laboratory and clinical data is not easily applied to modern merchant ship bridge conditions, conduct research to produce appropriate adaptation data using the expected pre-adaptation light level (e.g. ship corridor lighting level) and post-adaptation light level (i.e. bridge ambient light level) measured in this project.

- Examine the benefits of Electronic Chart Display and Information Systems (ECDIS) in relation to the management of dark adaptation.

- Examine the use of red light/ red filtered goggles to maintain dark adaptation of the rod photoreceptors of the eye.

With respect to individual characteristics:

- Limit daytime exposure to direct sunlight, i.e. wear sunglasses.

With respect to the bridge environment:

- Reinforce current standards (i.e. 15 minute recommendation) regarding dark adaptation.
- Reinforce lighting standards contained in the ergonomic criteria for bridge design.
- Limit the time spent performing lookout duty.

With respect to the external environment:

- Examine the configuration and specification of navigation lights in respect of small craft.

With respect to current regulations and guidance:

- Examine the scope for adding measures of sensitivity to contrast under mesopic and scotopic conditions to the seafarer’s eye test.
- Examine the scope for selecting Lookouts on the basis of mesopic and scotopic vision tests.
- Examine the scope for the introduction of visual search training.

1 INTRODUCTION

A recent report by the Marine Accident Investigation Branch (MAIB)[1] into the loss of a sailing yacht believed to be in a collision with a larger vessel, identified three key factors that could have reduced the Lookout's (dark adapted) night vision, and in turn contributed to the failure of the Lookout to detect the presence of the yacht. These were:

- An insufficient period of dark adaptation to the night watch environment;
- Light pollution in the wheelhouse; and
- The wearing of photochromic lenses at night.

The safe and efficient conduct of the vessel and its protection against external dangers such as collisions, groundings and dangerous hydrological or meteorological conditions, is a central objective of the navigation process. At all times, safe navigation requires effective command, control, communication and management. The Officer of the Watch (OOW) has operational responsibility for the navigational watch including maintaining a proper lookout by sight and by hearing, as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision. The role of the Lookout is to support the OOW by keeping lookout for other ships (especially those in distress), navigation marks, floating debris and other potential dangers to navigation that may cross the ship's path. The lookout task is primarily a visual search task that involves the active scanning of the visual environment for the navigation lights of other ships, which may appear as no more than specks of light on the horizon.

Current legislation (Standards of Training, Certification and Watchkeeping [STCW] A-VIII/2 Part 3-1, paragraph 19) states with respect to dark adaptation:

> *"The relieving officer shall ensure that the members of the relieving watch are fully capable of performing their duties, particularly as regards their adjustment to night vision. Relieving officers shall not take over the watch until their vision is fully adjusted to the light conditions".*

The key factors in determining the Lookout's ability to detect the navigational lights of other ships are the luminous intensity of the light to be detected, the meteorological visibility and the threshold of illuminance at the eye of an observer. The threshold of illuminance at the eye is determined by the ambient lighting conditions on the bridge and the dark-adapted state of the Lookout. Ambient light includes both naturally occurring light, such as, moonlight, light pollution from the deck lights and the lights of other ships and portside lighting, among other sources. Dark adaptation is the improvement of visual sensitivity that occurs when the ambient light level is decreased. However, current

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[1] *Marine Accident Investigation Branch (2007). Report on the investigation of the loss of the sailing yacht Ouzo and her three crew, South of the Isle of Wight during the night of 20/21 August 2006. Report no 7/2007. Published 12 April 2007.*

regulations fail to specify either a time period that is sufficient for dark adaptation to occur, or the means by which night vision should be evaluated.

1.1 AIMS

This research project aims to clarify and quantify the demands of the working environment and watch-keeping regime for large commercial ships in relation to dark adaptation and other factors that can influence the performance of a night time Lookout, such as age, health, working routine, safe manning hours and fatigue.

1.2 OBJECTIVES

The objectives of this research were to:

1. Based upon STCW Section A-VIII/2 part 3, and in particular part 3-1, conduct a task analysis of night time lookout duties, to identify the demands in relation to dark adaptation and levels of night-vision, in the environment of the bridge of a merchant ship.

2. Consider the relevant available evidence on visual performance in relation to Dark Adaptation and other aspects of night time vision.

3. Prepare a report summarising the findings of the task analysis and the relevant existing evidence on visual performance and any additional observations relevant to dark adaptation from the work undertaken and, where relevant, make recommendations in relation to best practice for bridge management and safe operating procedures for night time bridge lookout duties at sea.

2 METHODS

2.1 LITERATURE REVIEW

2.1.1 Search Strategy

Web of Science, Medline, Embase and Psyclit, HSELINE, NIOSHTIC, CISDOC, RILOSH and OSHLINE; RoSP, NIOSHTIC and CISDOC MEDLINE were searched for published, peer-reviewed studies on visual performance in relation to dark adaptation and other aspects of night time vision, using the key words:

- Dark adaptation
- Dark adaptation and ageing
- Rhodopsin
- Re-adaptation
- Night myopia
- Ships bridge
- Night vision
- Night vision and red light

Web searches using the Google scholar search engine and similar key words were performed periodically to ensure that relevant current reports were not missed.

2.1.2 Exclusions

The search for dark adaptation produced over 3000 articles; therefore the search was refined to identify papers where:

- The words night or dark appeared within five words of eye, sight or vision, which appeared within five words of adapt, adjust, change, or changing;

- Dark with adapt appeared within five words of adjust, change or changing;

- The new search produced 216 articles. The abstracts were reviewed and those that were not relevant, too specific, or did not focus on dark adaptation were excluded.

2.2 SHIP VISITS

The following ship visits were undertaken during this investigation.

1. **Task familiarisation at Lairdside Maritime centre (LMC):** A pilot exercise was conducted using the LMC full mission ship bridge simulator. The aim was to observe training and operation of the bridge in an ecologically valid setting in order to become more familiar with the practical demands of the duties associated with night time lookout, the

bridge layout and environment. This pilot exercise was used to test the data collection methods within the bridge environment and to identify potential performance influencing factors.

2. **Visits onboard two roll-on, roll-off and passenger ferries (RoPax):** The author, accompanied by Bert Kunze (Lairdside Maritime Centre) and Dr Peter Howarth (Loughborough University), completed a return journey onboard two separate roll-on, roll-off and passenger ferries (RoPax) to observe the activities associated with maintaining a safe navigational watch at night. The larger of the two ships was 26,500gt, with room for 980 passengers and 121 cabins. Both RoPax vessels had forward located closed bridges and operated a '6 hours on, 6 hours off' watch rotation (a typical watch pattern on short sea trade vessels). The vessels observed shuttle between ports, on relatively short routes with a typical turnaround time of four hours. During the ship visits the Master of the Ship accompanied the researchers and informed the bridge crew about the project and why they were being observed.

3. **Visit onboard an oil tanker:** The author accompanied by Bert Kunze completed a one-way journey onboard an oil tanker (56,204gt). The oil tanker was a much larger vessel that makes far longer voyages than either of the RoPax ferries and as such operates a traditional four-hour watch rotation. Observation of ships with different shift patterns help to ensure that any differences in practice of night time lookout duties are captured. Furthermore, fatigue has the potential to influence vigilance performance and observing different shift patterns ensures this factor is adequately covered. The oil tanker has an aft (rear) located bridge with open bridge wings; selection of this design was deliberate in order to ensure differences in bridge activities between different ship types were captured.

2.2.1 Data collection

The study methods used during the ship visits incorporated:

1. **Informal, unstructured interviews:** These were conducted with members of the bridge crew responsible for maintaining a safe navigational watch, in order to obtain further insight into the task requirements and performance-influencing factors.

2. **Video footage:** Observation of night time duties on the bridge was recorded on videotape for later analysis. The observation commenced before the start of the watch shift to ascertain the length of time taken to complete the watch change and the general procedure for such changes. In this instance, video recorders with infrared capability were used, as they allow for the unobtrusive observation of operators in their work environment, without impacting on their ability to perform a task that is safety-critical in nature.

3. **Light survey:** Measures were taken of luminance and illuminance of equipment and the environment within the operator's field of view on the bridge and in adjacent corridors and areas outside the bridge. This was to provide environmental data of an operational bridge under night time conditions to determine the level and direction of light on the bridge that operators are exposed to.

4. **Examination of documents:** Current legislation and archival data, such as copies of operating procedures and manuals, and job descriptions for maintaining a safe navigational watch at night, were examined in order to identify best practice procedures.

5. **Review of appropriate legislation:** The International Maritime Organisation (IMO) has developed a wide range of international conventions aimed at the prevention of accidents, including The International Convention for the Safety of Life at Sea (SOLAS) (1), The Convention on the International Regulations for Preventing Collisions at Sea (COLREGS), (2) and The Standards of Training Certification and Watchkeeping for Seafarers (STCW 78), as amended (3).They have been identified as those most relevant to maintaining a safe navigational watch, forming the basis of many standard operating procedures and 'best practice', and as such will be referred to throughout this report.

Quantitative data on the objects in the external environment, i.e. objects that the Lookout is looking at, was not collected for both practical and pragmatic reasons. The navigational lights of a yacht viewed at a distance will provide light that is characterised as coming from a "point source". Although, like a star, the lamp isn't actually a point, the light is treated as having come from one because the distance involved is so large relative to its size that the light behaves as having come from a point. There are technical issues regarding the measurement of light levels at the distances described in COLREGS, as light meters are not sensitive enough to accurately quantify point sources at these distances (upwards of 2 miles).

The measurement of stars is not performed using normal light meters, but rather involves photographic techniques, and these techniques could have been employed to measure the environment had it been considered appropriate. However, these measurements would tell us little about the probability of the Lookout spotting a lamp, because its characteristics are already known. Annex 1 of the COLREGS states that vessels of less than 12 metres in length must display a masthead light that is visible at a distance of 2 miles; and the impact of the external environment on the luminous intensity of such lights can be estimated using Allard's Law (see section 7.4).

Although the likelihood of detecting the light will be a function of amount of light given off by the navigational light, this measurement has little value in isolation because; the comparison that is relevant is between, the stimulus and the sensitivity of the observer. Hence the relevance of the external environment, in this context, is in the influence it will have in determining the adaptation state of the eye. The luminance readings of the external environment that were taken were so low that it was apparent that the lookout's adaptation level would be set by the internal conditions of the bridge, and not by the external environment.

Although there has been considerable laboratory research into the threshold detection of spots of light, this has been performed under conditions in which the adaptation state of the eye is set by the background conditions. In the practical context we are considering here the adaptation state of the eye is set by the ambient conditions and not the background conditions. Consequently, there is a lack of comparable data in the visual performance literature against which to benchmark any results, and as such there is limited utility in trying to collect such data at this time.

The focus of this report is on the impact of dark adaptation on performance of the Lookout task and therefore focuses on what can be influenced to improve the likelihood of detection, i.e. the ambient light levels on the bridge, and increasing the sensitivity of the Lookout.

2.2.2 Data analysis

The data analysis was performed by the author and involved:

- Reviewing the notes of the informal interviews with the bridge crew taken during the ship visits, in conjunction with an analysis of both the video and documentary evidence collected, to develop a Hierarchical Task Analysis (HTA) of the activities associated with maintaining a safe navigational watch. HTA is a top down action-oriented approach in which system goals (i.e. desired states of the system under control or supervision) are re-described in terms of a set of sub-goals, operations or actions, and organised using a series of plans specifying the conditions under which the subordinate goals are carried out to meet the system goal in question.

- Using a link analysis to describe the relationship between lookout duties and the equipment on the bridge, including: exposure to light source that could affect visual performance both on and off the bridge. This approach provides valuable information on the work areas most frequently used by the Lookouts, and the interactions with the various areas of the working environment.

- Conducting a light exposure assessment considering the layout of the bridge, equipment used and exposure to light sources, all with reference to the measures of luminance and illuminance taken onboard.

- Considering the task requirements, performance-influencing factors and the interactions between these to identify good practice associated with bridge night time lookout, in relation to the statutory requirements.

3 EXISTING KNOWLEGDE ON DARK ADAPTATION

3.1 HUMAN VISION

Human vision involves the capacity of the eye to adapt to variations in ambient illumination. The eye can function from very dark to very bright levels of light; its capabilities reach across more than 10 orders of magnitude (4;5). The average luminance of the visual scene that can be accommodated ranges from roughly 0.000001 cd/m^2 on a very dark night to around 100,000 cd/m^2 on a bright sunlit day (6). Table 1 gives typical values of the luminance in different environments.

Table 1 Typical luminance levels

Condition	Luminance (cd/m^2)
Starlight	0.00001
Full moon	0.001
Indoor lighting	100
Outdoor shade	10,000
Bright sunlit day	100,000
Direct sunlight	1,000,000
The Sun	10^8

Dark adaptation is the improvement of visual sensitivity that occurs when the ambient light level is decreased (7). In the first instance, the pupils increase in size at low illumination levels and contract in bright light to control the amount of light entering the eye (8). The change in the size of the pupil that occurs with changes in intensity of illumination allows up to a 16-fold increase in the area of exposed lens (9). However, constriction and dilation of the pupil cannot fully account for the wide range of illuminance that the human retina encounters. Therefore, our ability to adapt to changing levels of ambient lighting is reliant on a number of complex processes that involve the sequential progression of anatomic, photochemical and neurophysiological events. These include increased photosensitivity of the retina, conversion from cone to rod vision and a shift in the neural pathways within the retina (5;7;9).

3.1.1 Duplicity theory

Central to any discussion of dark adaptation is the duplex nature of the anatomical organisation of the human retina (10). The duplicity theory of vision (11) is based on the fact that the human retina contains two different photoreceptors, rods and cones, which function independently of each other, operating under different conditions, and giving rise to qualitatively different perceptions (12). The average human retina contains 4.6 million cones and around 92 million rods (13). In the periphery, the rods dominate; more centrally the relative number of cones increases and in the fovea, the visual centre of the eye, there are virtually only cones (14). A graphical representation of the spatial density of rod and cone photoreceptors within the human retina is shown in Figure 1. Cones facilitate day vision, colour vision and provide more detailed spatial resolution. Rods facilitate night and peripheral vision, but have relatively poor ability to discern detail or motion and are insensitive to colour (15).

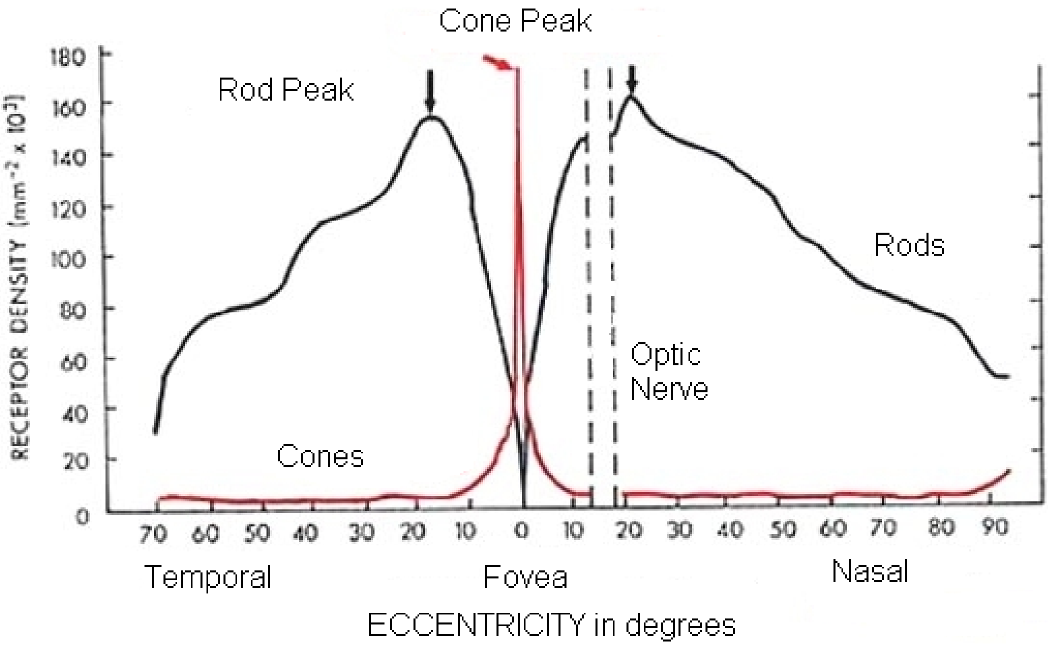

Figure 1 Distribution of rods and cones in the human eye. From G. Osterberg (13)

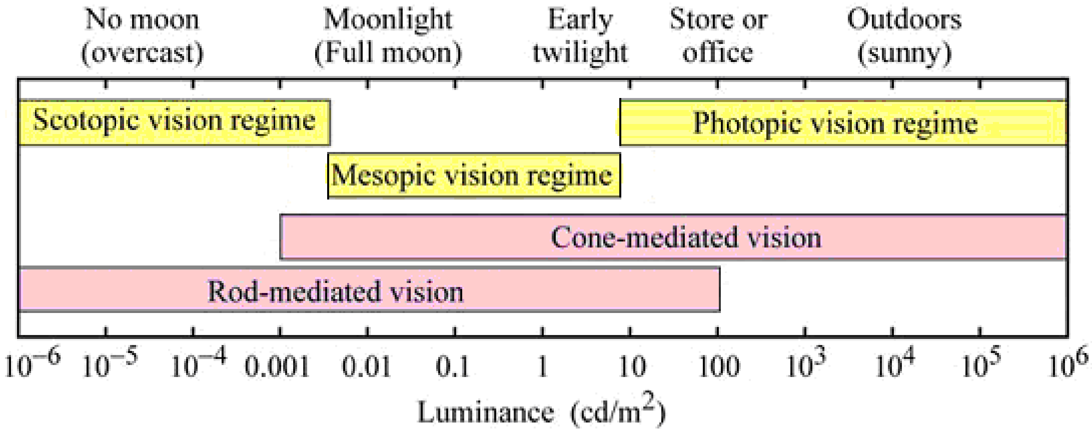

Figure 2 Range of conditions that can be accommodated by the human eye (From 16)

Rods and cones function exclusively within certain illumination ranges (5). Under reduced illumination, ambient lighting below 0.03 cd/m^2 (candela per square metre), rods cells are functional and exclusively mediate vision; this is referred to as scotopic vision (17) (often, incorrectly, termed ‘night vision’). As the light increases, rod function starts to decrease and the cones begin to operate. Once luminance increases sufficiently, so that only cones are functioning, the visual system is operating in the photopic range. The transition between photopic (cones) and scotopic (rods) vision is gradual; both the rods and cones as well as the adaptive mechanism of each system interact in the mesopic range (9). Figure 2 illustrates the range of conditions that can be accommodated by the human eye.

3.1.2 Classic Dark Adaptation Curve (DAC)

A clear illustration of the duplex nature of the visual system is shown in the classic Dark Adaptation Curve (DAC) reported by Hecht and Mandlebaum (18), who observed a two stage decrease in visual threshold with time after initial pre-adaptation to a very bright light source. The methodology used to obtain a DAC typically involves pre-exposing participants to a very bright light source, so that they become fully light adapted, after which the light is turned off (an instant called time zero), and a test flash is presented at various intervals to designated retinal locations. The minimum luminance (threshold) required to detect the test flash is determined by adjusting the intensity of a target stimulus (usually a small test flash of less than 1 second) until participants can just see it. Threshold is measured using the method of ascending limits (from non-seeing to seeing). The first observation is made within the first 15 to 30 seconds after the termination of the bleaching light, and then as many readings as possible are taken until a stable threshold is obtained. It is widely accepted among the scientific community and has been consistently replicated using a variety of methods and populations (5).

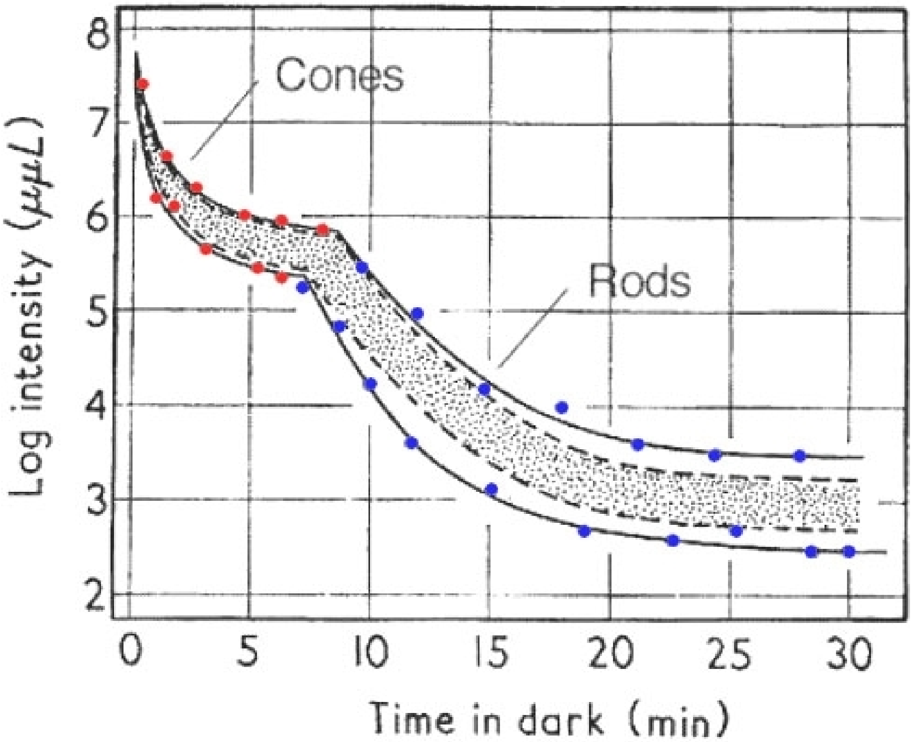

Figure 3 Dark adaptation curve. Hecht and Mandelbaum (1939). From Pirenne M. H., Dark Adaptation and Night Vision. Chapter 5. In: Davidson, H. (ed), The Eye, vol 2. London, Academic Press, 1962

Figure 3 illustrates the time course of dark adaptation; the shaded area represents the data for 80% of Hecht and Mandlebaum's participants (N = 110 university staff, students and volunteers). Time is plotted on the horizontal axis on an ordinary linear scale. Light intensity, however, is plotted on the vertical axis on a power or logarithmic (base 10) scale. On such a scale 1 means 10 units, 2 means 100 units, 3 means 1,000 units, etc. (see Box 1 for a definition of the units used in photometry).

The first phase of the curve reflects the fact that, after exposure to a bright light (providing a strong bleach), the rods are relatively insensitive and it is the cone system which is the more sensitive of the two. As a consequence, it is the cone system that is initially the active system in determining the threshold for the detection of the light. Depending on the strength of the bleach, the first phase may take around 5 to 10 minutes to complete, approaching a minimum threshold in the mesopic range (12). Phase one of the curve was originally conceptualised as a hypothetical limit obtained if cone activity could be measured independently of rod activity, and making the basic assumption that the potential cone threshold reaches a stable plateau level after a few minutes of dark adaptation (19).

More recent research has supported this position, for example, Stabell and Stabell (20) report that the DAC of the rod-free fovea reached a stable plateau after approximately 8 minutes. After around 5-10 minutes in the dark, the rod-cone break occurs, i.e. the sensitivity of the rod pathway improves to the point where the rod system becomes the more sensitive of the two (21). This is reflected by the second part of the DAC (often referred to as the S2 component), wherein the rods require around 30 to 45 minutes to effectively reach their minimum (absolute threshold) of around 10^{-5} cd/m^2 (12). Further evidence to support the rod-cone break is again provided by Stabell and Stabell (22) who demonstrate changes in the perception of colour during dark adaptation. During the cone-plateau period, the colour mixture functions remained invariant. However, at the point where the rod-cone break was observed, the perception of colour changed. When the rod mechanism takes over, coloured test spots appeared colourless and, as such, it can be concluded that the second component of the DAC is due to pure rod activity as only the cone pathway provides the sensation of colour (15).

Box 1 Photometric quantities and units of measurement

Photometry has a long history that has generated a number of different units of measurement for illuminance and luminance (defined in Table 2). Table 3 lists some of these obsolete units, together with the multiplying factors necessary to convert from the alternative unit to the SI units of lumens/m^2 (23).

Table 2 Photometric quantities

Measure	Definition	Units
Luminous flux	The quantity of radiant flux which expresses its capacity to produce visual sensation	Lumens (lm)
Luminous intensity	The luminous flux emitted in a very narrow cone containing the given direction divided by the solid angle of the cone, i.e. luminous flux/unit solid angle	Candela (cd)
Illuminance	The luminous flux/unit area at a point on a surface	Lumen/m^2
Luminance	The luminous flux emitted in a given direction divided by the product of the projected area of the source element perpendicular to the direction and the solid angle containing that direction, i.e. luminous intensity/unit area	Candela/m^2

Table 3 Photometric units of measurement

Quantity	Unit	Dimensions	Multiplying factor
Illuminance	Lux	Lumen/m^2	1.00
	Metre candle	Lumen/m^2	1.00
	Phot	Lumen/cm^2	10,000
	Footcandle	Lumen/ft^2	10.76
Luminance	Nit	Candela/m^2	1.00
	Stilb	Candela/cm^2	10,000
		Candela/in^2	1,550
		Candela/ft^2	10.76
Luminous exitance[1]	Apostilb	Lumen/m^2	0.32
	Blondel	Lumen/m^2	0.32
	Lambert	Lumen/cm^2	3,183
	Footlambert	Lumen/ft^2	3.43

[1] Luminous exitance is the product of the illuminance on the surface and the reflectance of the surface. It is only meaningful for completely diffusely reflecting surfaces. Luminous exitance has the dimensions of lumens/unit area. Luminous exitance is deprecated in the SI system.

A further unit referred to in the discussion of dark adaptation is the Troland (c.f. photon). The Troland (Td) is a unit of retinal illuminance, equal to the retinal illuminance produced by a surface whose luminance is one nit when the apparent area of the entrance pupil of the eye is 1 mm^2 and can be calculated using the following formula:

Photopic luminance (Candela/m^2) x Pupil size (mm^2)

3.1.3 Changes in stimulus dimensions = changes in dark adaptation

In is important to note that the shape and time course of a dark adaptation curve is dictated primarily by the duplex anatomic structure of the retina and the extent to which rods, cones, or both are influenced by the adapting light and by the test flash (5). Fundamental differences exist between experimental laboratory studies that measure light threshold of the dark adapted eye (9) and substantial variations can occur with small changes in stimulus dimensions. In any determination of a DAC, the actual value of threshold intensity will depend upon the size, duration, wavelength etc of the test flash (21;24-30).

Particularly relevant in the examination of the lookout task is the intensity of the pre-adapting light source. It is highly unlikely that the bridge crew will, immediately prior to commencing night time lookout duties, be exposed to a light source comparable to those used in the laboratory study of dark adaptation. They are far more likely to adapt from much lower levels of light and, as seen in Figure 4, decreasing the light levels prior to adaptation reduces the initial threshold of detection and decreases the time taken to reach both the rod-cone break, and the minimum detection threshold (31). Furthermore, if the adaptation light source was 3,000 Td or less, only the rods are sensitive enough to detect the test light, as evidenced by the absence of a rod-cone break, and significant improvements in minimum threshold occur during the first 10 minutes, and the final steady-state level is almost reached after about 15 minutes.

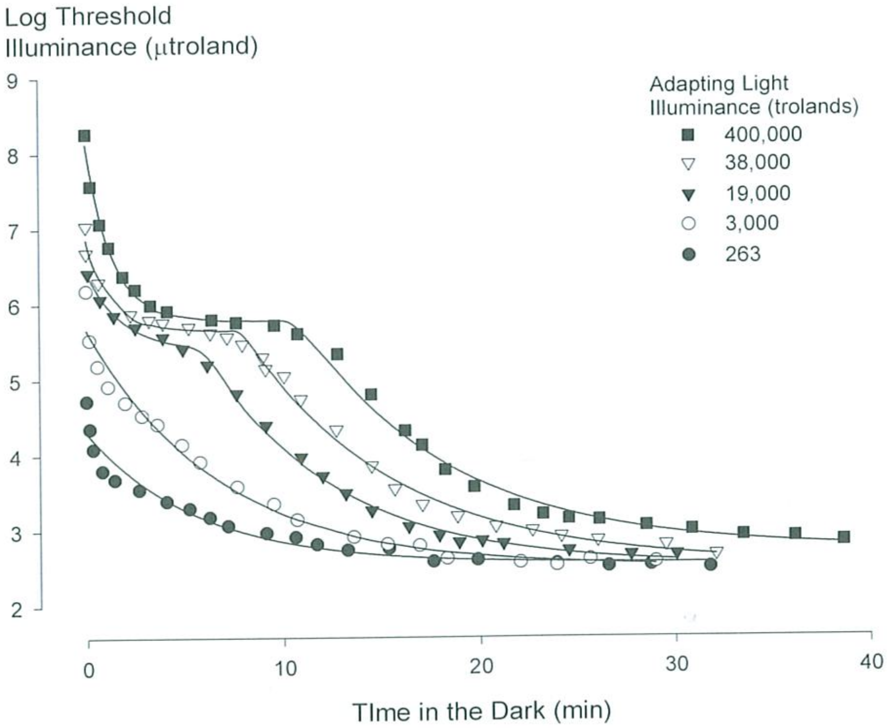

Figure 4 Dark adaptation curves following different levels of pre-adapting luminance (In 5; Modified from 31)

Summary
Dark adaptation is the improvement of visual sensitivity that occurs when the ambient light level is decreased. The human retina contains two different types of photoreceptor: rods and cones. After an intensive bleach, cone receptors take around 10 minutes to reach their minimum threshold and rods require around 45 minutes to reach their absolute threshold of around 10^{-5} cd/m^2. The lower the levels of pre-adaptation light, the faster the rate of dark adaptation. At low ambient levels it can be the rods and not the cones which are the more sensitive of the two systems, and at low luminance levels (below 0.03 cd/m^2) only rods cells are sensitive to light and exclusively mediate vision.

3.2 THE ROLE OF RHODOPSIN IN DARK ADAPTATION

Much of dark adaptation can be explained by a simple photochemical process in which the photopigment rhodopsin (originally referred to as visual purple) is bleached away during exposure to a bright light, and is re-synthesised in the dark (7). Rhodopsin is a chemical combination of vitamin A (in the form of 11-*cis* retinal) and an opsin, a group of light sensitive protein receptors found in the retina (12). Rushton et al (32) used retinal densitometry, which allows the level of visual pigment to be measured in the living eye during bleaching and regeneration, to plot the time course of the regeneration of human rhodopsin; they found that it takes around 40 minutes following a full bleach to completely regenerate. Similarly, the level of photopigment in the cones (chromopsins) return to normal in around 8 minutes (33). Both these times correspond closely to the times detailed in the classic dark adaptation curve shown in Figure 3, which strongly suggests that there is a direct relationship between threshold and the concentration of photopigment. Furthermore, Rushton (21) illustrates that despite very different extents of bleaching and subsequent periods in the dark, the rod-cone break appears to occur when around 92% of rhodopsin has been re-synthesised. This is summarised in Figure 5, which shows that after total bleach (O), the moment when the rods are first sensitive enough to respond to a green flash occurs after around 15 minutes, corresponding to the 92% threshold. Subsequent repetitions with weaker pre-adapting light (O = 25%, ● = 35%) produced shorter adaptation times. However, when adjusted so that the first point of the curve (zero time) falls onto the exponential curve, not only do all subsequent points lie upon the same curve, but the point when participants first respond to the test stimulus is the same, i.e. 92% rhodopsin. Additional evidence of the link between the recovery of visual sensitivity and the regeneration of rhodopsin can be found in Lamb and Pugh (34).

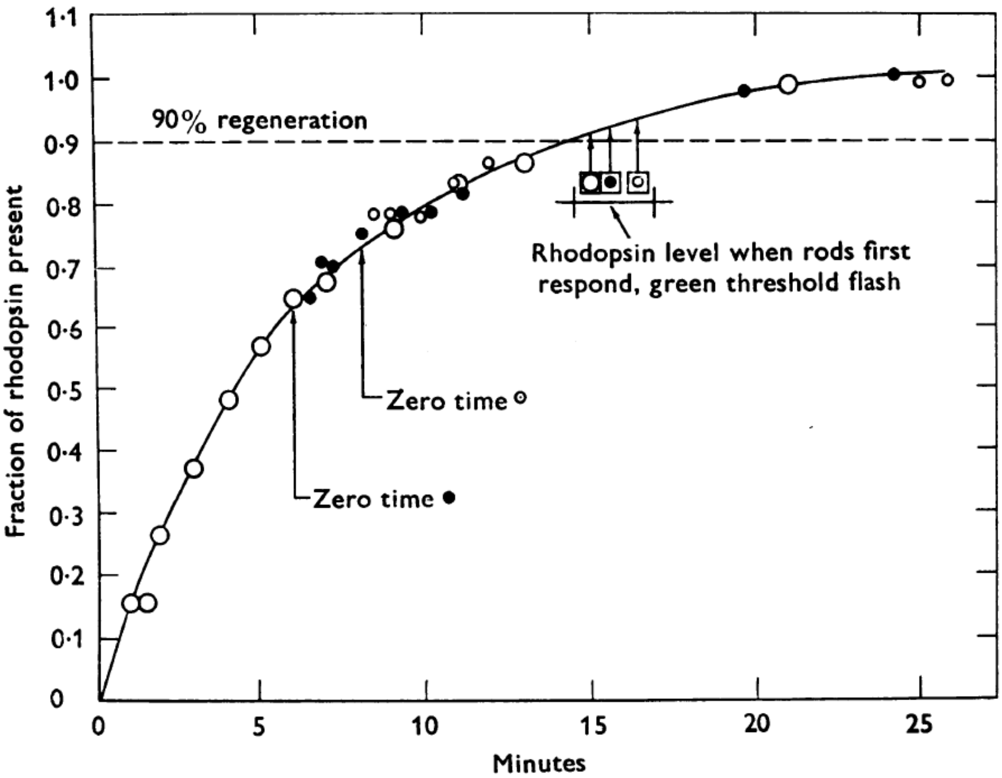

Figure 5 Regeneration of rhodopsin during dark adaptation. The rod-cone break for each condition is marked with an arrow (21)

Summary
Dark adaptation in rods can be explained by a simple photochemical process in which the photopigment rhodopsin is bleached away during exposure to a bright light, and is re-synthesised in the dark. The full regeneration of human rhodopsin takes around 40 minutes following full bleach. The rod-cone break occurs after 5-10 minutes, when around 92% of rhodopsin has been re-synthesised. Weaker pre-adapting lights, which bleach far less rhodopsin, produce shorter adaptation times.

3.3 NEURAL ADAPTATION

Adaptation in the eye not related to the visual pigment level is usually referred to as neural adaptation (35). There are aspects of visual function that change during dark adaptation that cannot readily be accounted for in terms of photochemical changes, but reflect changes in the response of the photoreceptors and the cells that receive input from the photoreceptors (5). Rapid neural adaptation has been observed during the initial stages of dark adaptation when measured from the increment or instantaneous threshold level (7;36;37). For example, Baker (38) examined the threshold for detecting the test flash within 2 seconds after time zero and found that there is a rapid decrease in threshold within 0.3 seconds after the adapting flash was turned off (57, 1,800 and 57,000 trolands for 20 milliseconds centred on the fovea).

Lythgoe (39) first drew attention to the fact that lights which bleach only a small fragment of visual purple (rhodopsin) could still cause very big changes in threshold and suggested that the change is in part due to the alteration of nerve organisation. It was hypothesised that the decreasing ability to perform fine visual judgements under scotopic conditions may be due to synaptic rearrangement. During complete light adaptation, each visual element is served by separate nerve fibres, which make the individual capable of performing fine judgements, while during dark adaptation each fibre serves several elements by a spread of its synaptic connections, which reduces discrimination of fine detail but improves retinal sensitivity to light.

It is generally agreed that a rod can be excited by the catch of a single quantum (40). That is, 1 quantum of light absorbed can excite a dark-adapted rod in the human eye and a fully dark-adapted human subject is capable of detecting as few as 5–10 photon absorptions occurring within a short time interval anywhere over a 'pool' of around 10,000 rods (41;42). Therefore, adapting lights 70,000,000 times above the visual threshold should not bleach away more than 2 per cent of the visual pigment in a rod over the course of a 5 second exposure, raising the visual threshold by less than 0.5 of a log unit (35). Yet evidence suggests that adapting lights of this luminance raise the human visual threshold 2 to 3 log units when measured at the beginning of dark adaptation (43-45). Rushton (46) hypothesised that rod signals converge upon a 'summation pool' (illustrated in Figure 6), which responds to the total flux of signals, independent of the particular rods excited. Whenever a rod absorbs a quantum it generates one signal that travels to the 'summation pool'. If a critical number of signals (*N*) arrive at the pool within a short time interval, a message will be relayed to the brain and the light will be seen. The total flux of these messages modifies the sensitivity of the pool and determines the sizes of flux increment needed for detection (47).

Further evidence of neural changes during dark adaptation can be found in a consideration of a number of studies that suggest adaptive effects can spread laterally across the retina. Illumination in one area of the retina has been shown to elevate thresholds for test stimuli falling on areas that have not be directly exposed to light (47-51). For example, Lipetz (52) projected a small conditioning spot onto the excised retina of a bullfrog for several minutes and then measured the ganglion cell thresholds for a test stimulus at the previously illuminated area and at an unilluminated area. The unilluminated area showed an increase in threshold, which was greater than could be explained by scattered light.

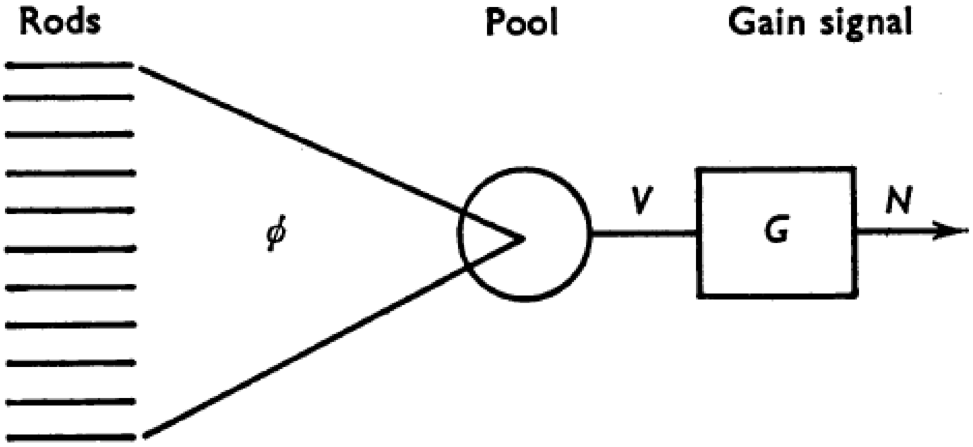

Figure 6 The effect of a flash of light (Ø), the pooled rod response (V) is modified by a variable gain box (G) to produce the output (*N*)

Rushton and Westheimer (53) were able to reach similar conclusions in experiments on man. The aim of their investigation was to find out whether the rod threshold rises after bleaching rhodopsin because (a) the rods need more light to generate a signal, or (b) because the summation pool needs more signals to activate the optic nerve. To achieve this, a grating of black and transparent stripes of equal size was focused upon the retina so that the retina was 'bleached' and 'spared' in parallel strips and was compared to a second similar region of the retina bleached using a neutral density of 0.4, designed to transmit the same total light as the grating. Dark adaptation in the two regions was measured with the test flashes reversed, i.e. the uniformly bleached area was tested with the grating interposed, and the stripe-bleached area with the density filter interposed. Results show that the loss of sensitivity after bleach is not confined to the area exposed to the adapting light source, and the two dark adaptation curves were practically identical. The results did not support mechanism (a), that the rods need more light to generate a signal, as the strip of retina that lay under the dark bar of the grating image received less illumination than the rest of the test spot, yet threshold levels were not detectably lower. This suggests that the threshold of a rod may be raised by bleaching the rhodopsin of neighbouring rods, which would be expected if the factor that changes during dark adaptation is the threshold of the pooled rod signals, i.e. mechanism (b). In sum, these experiments appear to establish that, as Rushton (46) hypothesised, changes in retinal sensitivity are controlled by signals pooled from many receptors (51).

It is now known that the synaptic ratio between the photoreceptors and bipolar cells, which transmit signals from the photoreceptors to the retinal ganglion cells that form the optic nerve, plays an important part in both night vision and visual acuity (12). The centrally located cones synapse 1:1 with the bipolar cells, and are ultimately represented individually in the cortex. As one moves more peripherally, a larger number of primary receptor cells synapse with each bipolar cell (54). Scotopic vision is mediated by two distinct pathways from rods to ganglion cells that operate at different light intensities (35). At higher scotopic levels, rod signals are electrically coupled via gap junctions to cones, and then follow the conventional photopic pathway via cone bipolar cells to ganglion cells. But at low scotopic intensities a separate pathway comes into play, capable of transmitting single photon responses. The rods synapse onto rod bipolar cells, which are functionally similar to cone bipolar cells (55). Under these conditions, if the rods are slightly stimulated, the summation of several low level stimuli may be enough to excite a bipolar cell, thus sending a ‘light’ signal to the brain (54).

Summary

There are aspects of visual function that change during dark adaptation that cannot readily be accounted for in terms of photochemical changes; adaptation in the eye not related to the visual pigment level is referred to as neural adaptation. Rapid neural adaptation has been observed during the initial stages of dark adaptation. It has been hypothesised that rod signals converge upon a ‘summation pool’, wherein if a critical number of rod signals arrive at the pool within a short time interval, a message will be relayed to the brain and the light will be seen. As such, the synaptic ratio between photoreceptors and bipolar cells (which transmit signals from the photoreceptors to the retinal ganglion cells that form the optic nerve) plays an important part in both night vision and visual acuity.

3.4 FACTORS AFFECTING DARK ADAPTATION

A number of other influences on dark adaptation and night vision performance were identified during the course of this study that may affect both the time course and the threshold sensitivity of dark adaptation.

3.4.1 Age-related changes in dark adaptation

Older adults often report problems performing visual tasks under dim lighting conditions and at night (56;57), for example, low illumination levels are a significant cause of age-related road traffic accidents (58-60). The dark adaptation process includes individual differences in the rate of dark adaptation and the final threshold of night vision capacity (9), and there is a considerable body of evidence that demonstrates the association between age and the process of dark adaptation. For example, McFarland et al (61) report a significant correlation of 0.89 between age and the minimum sensitivity threshold of 200 pilots between the ages of 20 and 60 years old (illustrated in Figure 7). Furthermore, the intensity of illumination at threshold levels had to be (approximately) doubled for each 13-year increase in age. On the basis of the observed relationship, it was possible to accurately predict the chronological age (+/- 3 years) of participants.

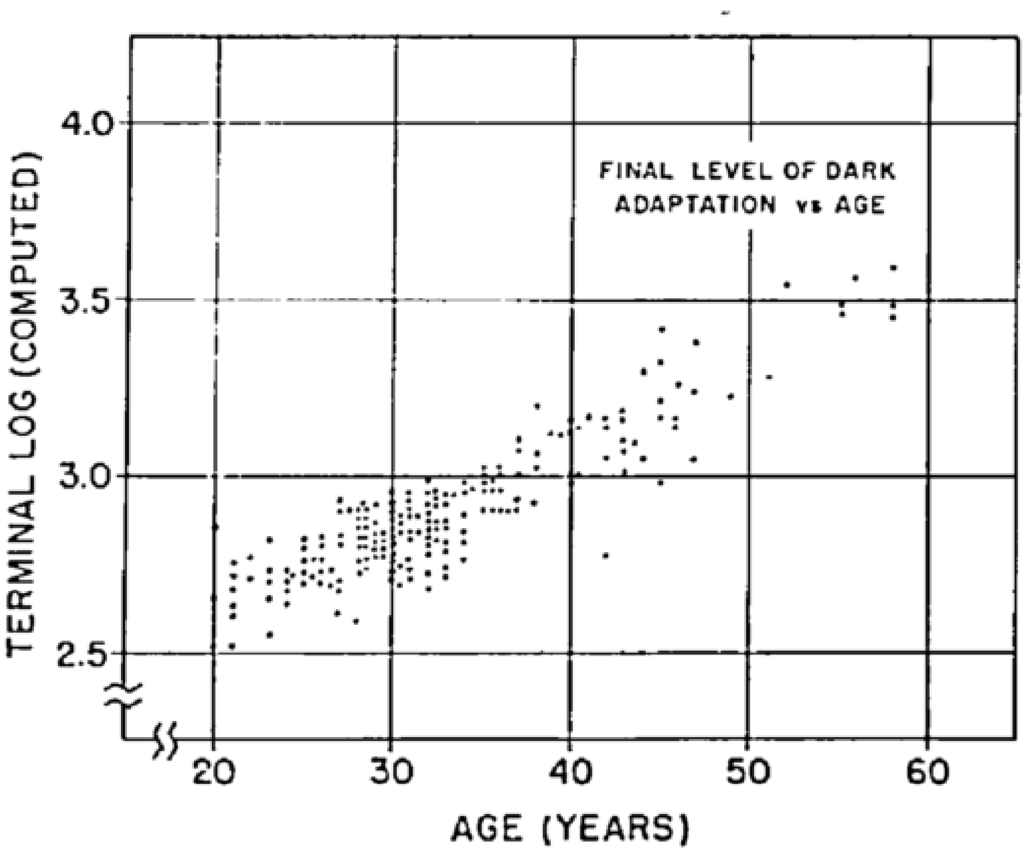

Figure 7 Scatter Diagram showing the relationship between the minimum threshold of dark adaptation and age (From 62)

Consistent with this finding, McFarland (63) found a significant difference in both the rate of recovery and minimum threshold sensitivity between the very old and the young (Participants aged from 16 to 89 years old). The correlations between age and final threshold at 2, 5 and 40 minutes were 0.71, 0.80 and 0.84 respectively. A compelling feature of this data is the extent to which the young and old differed. For example, at the second minute the youngest participants (16-29 years old) were five times more sensitive, and by the 40th minute were 240 times more sensitive than those in the oldest group (80-89 years old). This is illustrated in Figure 8. In this figure, the increase in threshold observed at around 41 minutes represents when participants viewed the test stimulus through a tinted windshield (reducing the amount of light reaching the retina by around 35%) as opposed to clear glass (the dotted lines). Other classic studies have revealed age-related reductions in minimum threshold sensitivity ranging from 0.3 to 2.0 log units in magnitude (e.g. 64;65;66).

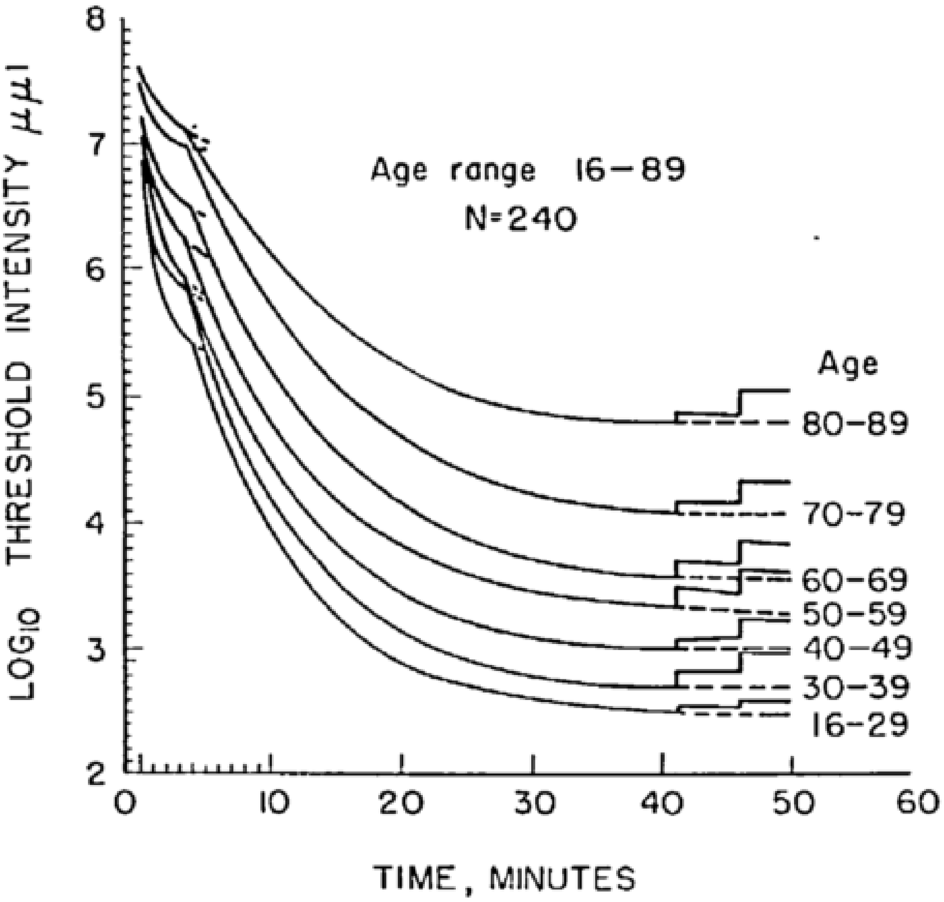

Figure 8 Average dark adaptation curves for seven groups of participants stratified by age (From 63)

Jackson et al (67) measured dark adaptation in young (mean = 27 years) and old (mean = 70 years) adults. Optical factors that might contribute to age-related reductions in performance such as ocular disease (examined using fundus photography), lens density, and pupil diameter were controlled. Participants who demonstrated good macular health (around 60% of older subjects exhibited fundoscopic signs of early age-related maculopathy) still demonstrated a 0.5 log unit loss in minimum threshold sensitivity with age. Similar findings were reported in a study by Sturr et al (68), in which rod sensitivity thresholds were found to be on average 0.39 log units higher in older participants (mean age 72.6 years) than in younger participants (mean age 24.1 years). This finding was consistent after correction for pupil size and lens density. Conversely, Herse (69) suggests that the rate of dark adaptation decreases with age in the cone photoreceptors yet remains relatively constant with age in the rod photoreceptors. Also the reduction in the rate of dark adaptation is due to a delay in the onset of the rod-cone break equivalent to a difference of 1.3 minutes between young (10-20 years) and old (60-80 years) participants. Collectively, these results suggest that impairment is representative of an underlying biological process.

Summary
Processes associated with increasing age have been shown to reduce the ability of individuals to detect light and increase the amount of time required for an individual to become dark adapted. There is a significant correlation between age and minimum sensitivity threshold, ranging from 0.3 to 2.0 log units. However, age alone would not determine the suitability of seafarers to undertake night time lookout duty.

3.4.2 Ophthalmic disorders

Ophthalmologic disorders have been identified as a significant factor affecting night vision capacity (9). For example, evidence suggests that the glaucoma group of disorders can impair both the time course and minimum sensitivity threshold of dark adaptation (70-73). Jonas et al (74) illustrate the extent to which optic nerve damage is associated with impairment of psychophysical functions. They measured dark adaptation in 19 patients with primary open-angle glaucoma in comparison to 4 patients with non-glaucomatous descending optic nerve atrophy and 14 normal participants. In the normal group, light thresholds and time of the shoulder in the dark adaptation curve increased significantly with age. However, in eyes with glaucomatous or non-glaucomatous optic nerve damage light sensitivity was poorer than in normal eyes of age matched control groups. Rod light sensitivity was significantly correlated with neuroretinal rim loss, parapapillary chorioretinal atrophy, and relative afferent papillary defects. Patients with glaucomatous and non-glaucomatous optic nerve atrophy show decreased light sensitivity especially during the rod-mediated phase of dark adaptation, worsening with advancing optic nerve damage.

The most common ophthalmic disorder to affect dark adaptation is age-related maculopathy (ARM). ARM is a progressive disorder of the macula (the centre of the retina) that usually affects older adults and results in a loss of vision in the centre of the visual field (75). Photoreceptor function is critically dependent on the retinal pigment epithelium (RPE) and Bruch's membrane to regulate the transport of nutrients, fluid, ions, and metabolites to and from the sub-retinal space (76). Characteristic changes in ARM include a progressive thickening of Bruch's membrane and the deposition of neutral lipids between the RPE and Bruch's membrane (77).

Evidence suggests that recovery of scotopic (dark adapted) vision after exposure to a pre-adapting light source occurs more slowly in patients diagnosed with ARM (78-80). For example, Owsley et al (2000) measured dark-adapted sensitivity of 80 patients with ARM. In comparison to the retina of normal, age matched controls; sensitivity was on average 6.7 dB[2] lower in ARM patients (Mean = 42.4, SD = 8.1 dB) than controls (Mean = 49.1, SD = 3.0 dB). Retinoid deficiency at the level of the photoreceptors has been suggested as

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[2] The decibel scale is a relative scale created by the manufacturers of automated perimeters to measure the sensitivity of vision. It is a logarithmic scale where 10 decibels are equal to 1 log unit; 20 decibels, to 2 log units, etc. Db are used to indicate the attenuation of brightness of the stimulus. Thus, a 20 dB stimulus is equal to one-tenth the brightness of a 10 dB stimulus.

the basis for the impairment of the dark adaptation function in ARM patients (81;82). This is because a scarcity of available vitamin A to combine with opsin to form rhodopsin would lead to a change in the rate of recovery after light exposure (83).

Owsley (84) examined the rod-mediated kinetics of dark adaptation in a group of participants (n = 20) diagnosed with early ARM and 16 adults in the same age range but free of ocular impairment. Dark adaptation functions were measured after exposure to the equivalent of a 98% bleach. Patients with early ARM exhibited deficits in almost all rod-mediated parameters of dark adaptation as compared with age-similar healthy participants. For example, the rod–cone break was delayed approximately 10 minutes in early ARM patients as compared with healthy participants. Furthermore, 85% of ARM patients fell outside the normal range for dark adaptation.

Consequently, it was hypothesised that increased systemic vitamin A concentrations may force additional vitamin A across Bruch's membrane into the RPE cells via mass action, which would in turn improve the dark adaptation function of patients diagnosed with ARM. Owsley et al (76) investigated the impact of a 30 day course of high dose retinol (50,000 IU) on dark adaptation in older adults in normal retinal health and those with early ARM in a double-masked, placebo-controlled trial. An improvement in the rate of rod-mediated dark adaptation was observed in both the ARM and normal retinal health groups that received the course of high dose retinol, in comparison to those receiving a placebo, as evidenced by a significantly steeper slope of the S2 region during the rod-mediated recovery of visual sensitivity after bleaching of the photopigment. Furthermore, participants in the retinol group demonstrated a significantly lower minimum threshold than participants in the placebo group after 30 minutes of dark adaptation, providing strong evidence that increased levels of vitamin A may overcome possible impairments in dark adaptation (8;9;85;86).

There are also a number of rare diseases that affect the timecourse and extent of dark adaptation including Fundus Albipunctatus (87-89), Oguchi disease (90-92), Sorsby Fundus Dystrophy (93-95), Bothina dystrophy (96-98) and Stargardt macular dystrophy (99-101). Lamb and Pugh (102;103) provide a comprehensive review of the ophthalmic disorders that impact the dark adaptation process. The current eyesight standards should pick up such disorders; therefore they should not be a significant performance-influencing factor.

3.4.3 Vitamin A

The regeneration of rhodopsin is functionally associated with the availability of retinal, a form of pro-vitamin A contained in plant tissues, e.g. carrots, tomatoes, and spinach which occur in several chemical forms, the most active of which is ß-carotene (9). As such, nutritional vitamin A deficiency (VAD) can interfere with rhodopsin production and can lead to night blindness (nyctalopia), an inability to see under dim or reduced light (104). Consequently, VAD is one of the most common causes of decreased dark adaptation (105). Van Graan et al (8) illustrated the impact of reduced availability of vitamin A on the dark adaptation process, correlating the serum vitamin A level of the blood and dark adaptation times in a group of mineworkers upon arrival and again after 4-6 months of continuous work underground. During the follow-up examination, decreases in mean vitamin A and carotene levels were associated with an increase in mean adaptation time, although the threshold light intensity did not change significantly. Similarly, Lamb and Pugh (106) show that the magnitude of the S2 component was significantly reduced in VAD patients to approximately 40% of normal.

Kin (86) examined the impact of supplemental vitamin A on the dark adaptation function of 60 air defence controllers and operators serving with the Singapore Air Force, in the belief that it would enhance the worker's ability to dark adapt. Such workers operate in pitch dark rooms that require good night vision and the capacity to accommodate rapidly changing levels of luminance (similar conditions to those observed onboard merchant vessels). The time course of dark adaptation was measured before and after a two-week course of vitamin A. Results support the notion that supplemental vitamin A enhances dark adaptation capability. Significant improvements in night vision performance were observed in terms of the time taken to adapt to specified levels of luminance, the time taken to maximally dark adapt and the final threshold of dark adaptation.

Cideciyan et al (107) compared VAD patients' rate of dark adaptation before and after a 10 week course of vitamin A supplements. Prior to the trial VAD patients exhibited abnormal recovery kinetics (the S2 component). After total bleach, complete recovery of the cones was delayed and took approximately 10 to 15 minutes and the rod cone break was delayed for approximately 40 minutes. The final dark-adapted rod threshold was not achieved for approximately 110 minutes, however final thresholds were within the normal range. The rapid increase in the availability of vitamin A for the synthesis of rhodopsin was associated with a rapid and significant improvement in dark adaptation recovery time. After 1 day of vitamin A supplement, cone recovery was complete within 8 minutes, the time to the rod-cone break was around 24 minutes and complete recovery of dark adaptation took around 80 minutes. Furthermore, after the 10-week period the S2 component returned to within the normal range observed in control group participants ($S2 = 0.24 \log_{10} \text{min}^{-1}$). Cone recovery was complete after 5 minutes, the rod-cone break occurred after 16 minutes and full recovery was achieved after 60 minutes. It is necessary to note that a course of supplemental vitamin A may not be beneficial to seafarers. There is a danger of vitamin A toxicity (hypervitaminosis A) associated with abuse of supplements and with diets extremely high in preformed vitamin A. Consumption of 25,000-50,000 IU/d for periods of several months or more can produce multiple adverse effects (108). However, it is reasonable to expect that they may benefit from a diet rich in ß-carotene (86), as the body will only convert as much vitamin A from ß-carotene as is needed (109).

3.4.4 Smoking/Carbon Monoxide (CO)

There is evidence that smoking can have a negative impact on the time course of dark adaptation due to the hypoxic effects of carbon monoxide (110-114). von Restorff and Hebisch (115) measured dark adaptation time and threshold sensitivity in five young healthy smokers and non-smokers during carbon monoxide (CO) exposure. It was found that mean dark adaptation time was longer and the light sensitivity of the eye was reduced in smokers as compared to non-smokers at comparable levels of CO exposure. Under control conditions smokers were found to take 20% more time to fully adapt than non-smokers. The maximum threshold of dark adaptation under these conditions was 50% higher in smokers than in non-smokers. Furthermore, while breathing 100ppm CO this time increased from 4.9 to 5.7 minutes in non-smokers and from 5.9 to 6.9 minutes in smokers. For both groups this is an increase of 16-17%.

Similarly, Calissendorff (116) found that dark adaptation performance after smoking was impaired in comparison to baseline measures taken prior to smoking. The difference was most noticeable during the first 10 minutes of measurement. However, this difference levels off over time and is no longer significant after 20 minutes; no significant impairment of the final sensitivity threshold was found. Contradictory evidence is provided by Wiley (117), who found no link between smoking and dark adaptation. Dark adaptation was measured in terms of absolute light sensitivity and rate of recovery after light exposure, in a population of 30 Army pilots (15 smokers, 15 non-smokers). Results showed no appreciable difference on any of the measures of dark adaptation between the smoking and non-smoking groups. Furthermore, other studies found that smoking appeared to improve night vision performance on some tests. This improvement was presumed to be a result of the stimulant effect of nicotine (114;118).

3.4.5 Red light and spectral sensitivity

The lookout task is a visual search task that involves the active scanning of the visual environment for the navigational lights of other ships (119). In the case of bridge personnel onboard a ship, cone-dominated foveal vision is used for the examination of instruments and charts, and rod-dominated peripheral vision is used when scanning the visual environment. For this reason it would be best to light instruments and chart tables with the colour of light to which the fovea is most sensitive and the peripheral region least sensitive (120). Furthermore, the sensitivity of dark-adapted vision can be rapidly reduced by exposure to a strong light source, as the eye will immediately begin to light-adapt (26;121-123). In the case of the bridge at night, impairment will depend on the nature of the light emission from displays and the general environment (12). It is therefore vital that as little light as possible should be allowed to enter the bridge in order to maintain the dark adaptation of the bridge crew. However, a certain amount of lighting is necessary as both the Officer of the Watch and Lookout must be able to see obstacles as they move about the bridge, and must be able to read the instrument displays, update maps and charts, as well as complete ship's logs at night. They may also need to move from a lit interior, e.g. the chart room, into an unlit environment, i.e. the bridge. It is therefore necessary to identify means of maintaining the dark-adapted vision of the bridge crew.

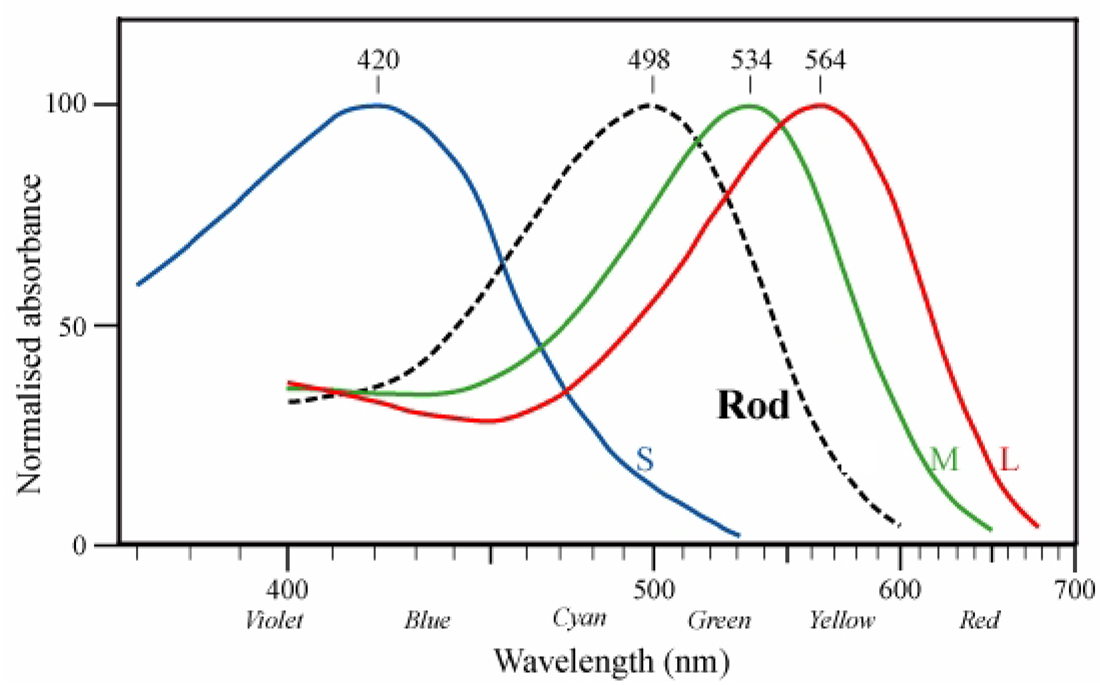

Figure 9 Receptor spectral absorbance, (124)

It is generally accepted that red light, or red tinted goggles, can preserve the dark adaptation of rods (125-129). Furthermore, the use of red goggles can reduce the amount of time spent adapting to the dark, as members of the relieving watch can still perform operational duties in well-lit areas of the ship while wearing red goggles; they can do very little sat in the dark. The rationale for the use of red light is based on the differences in spectral sensitivity between the rods and cones. Rods and cones are not equally sensitive to visible wavelengths of light (12;130). Figure 9 shows the normalised absorption[3] of rods and the three types of cone (short, medium and long wave), which differ in terms of wavelength. The cones are most sensitive to wavelengths of around 555nm (yellow-green), a primary reason why high visibility clothing is often ‘optic yellow’ as this colour will appear brightest under photopic conditions. The rods are most sensitive to light of the blue and green wavelengths (around 500nm), but are relatively insensitive to wavelengths greater than about 640nm, i.e. the red portion of the visible spectrum (15). As such, rods can be dark adapted in relatively high luminance conditions if the adapting wavelength primarily affects cones (12;124;131). Light above 640nm does not stimulate rods and so the rods are effectively in the dark while the person is using the red-sensitive cones to see (5).

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[3] Rods and cones do not absorb equal amounts of light.

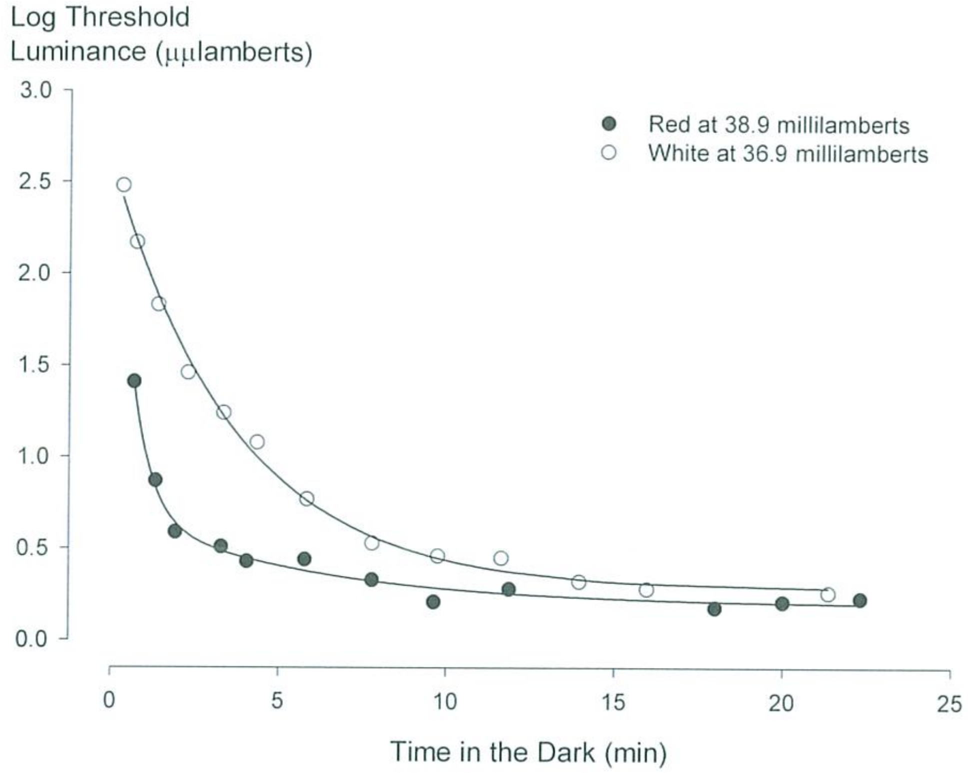

Figure 10 Average dark adaptation curves after light adaptation to a red or white adapting light of approximately the same luminance for 5 minutes. The test flash was short wavelength (blue), 3° in diameter, and 200 milliseconds in duration and was presented 7° nasal to the fovea. Modified from Hecht and Hsia, 1945 (From 5)

Hecht and Hsia (27) demonstrate the impact of red light stimulus on the rate of dark adaptation. Fully dark-adapted participants were exposed to either a red or white field of the same photopic luminance and the time taken to return to maximum threshold was measured. Subsequent dark adaptation was considerably faster after exposure to red light than after white light adaptation (as shown in Figure 10). Furthermore, it was found that the luminance of the red light could be 30 times greater than the white light and still yield the same degree of dark adaptation in the same length of time. Similarly, Connors (132) calculated recovery curves (i.e. time necessary to return to a predetermined dark adaptation threshold) following 1 and 5 minute adaptation to wavelengths ranging from 595 to 670 nm. After one minute of adaptation to a light of 610 nm, recovery was faster than after exposure to an equal light of 595 nm. Red light increases the speed at which the eyes become sensitive in the dark, however it does not remove the need to adapt in the dark.

Mitchell et al (133) found that pre-adaptation by wearing red goggles for long periods (20 minutes or more) produces very little dark adaptation compared with the same time spent in total darkness. The sensitivity threshold reached by wearing goggles for 40 minutes was 2.75 Log units above the threshold reached after 30 minutes in total darkness. However, red adaptation increased the rate of subsequent dark adaptation so that the 5 Log μμL threshold was reached in half the time after wearing red goggles for 5 minutes, and in a quarter of the time after 20 minutes in red goggles. Following red adaptation, time must still be spent in total darkness. Duration is dependent upon the outside darkness level e.g. for starlight (5 Log µµL) 8 minutes; for overcast starlight (4 Log µµL), 16 minutes.

The use of red light can create an unnatural visual environment and also create problems specific to seafaring. Waters and Ivergard (134) evaluated the performance of a group of trainee sea Captains on a series of navigation tests (plotting courses, taking distances and bearings, etc) conducted under four different lighting conditions (red at 4 cd/m^2 and white light at 0.5, 2.5 and 12.5 cd/m^2). Participants were marked for speed and accuracy by teaching staff. In terms of accuracy, performance was best under high white light (12.5 cd/m^2) and poorest under red, particularly where colour discrimination was required as the use of red light extinguishes any red detail that may be present on the chart. Similarly, the tasks were completed quickest under high levels of white light, however, low-level white light (0.5 cd/m^2) and not red was slowest. Subjective ratings regarding the level of eyestrain, difficulty associated with reading navigational charts and what they thought of the light in a real-life situation were collected from participants. From the analysis of responses it was clear participants disliked red light, which in all likelihood is related to participants' difficulty seeing the red detail on the chart. High white light was rated best. However, none of the conditions of white light that were tested satisfied all the subjective criteria for acceptance. Subsequently, the time course of dark adaptation was measured after completing the navigation task. It was found that adaptation was quickest under red light and slowest under bright white light, where it took on average three minutes longer to reach 0.5 Log above minimum threshold. Furthermore, naval officers (135) have reported an inability to discriminate colour coded information, as well as visual discomfort, headaches, focusing problems (particularly for older personnel) and difficulties in reading and log keeping. For these reasons many ships no longer use red lighting or red filters.

Summary

Red light can preserve dark adaptation. The rods are not sensitive to wavelengths greater than about 640nm, i.e. the red portion of the visible spectrum. Subsequent dark adaptation is considerably faster after exposure to red light than after white light adaptation. However, naval officers have reported an inability to discriminate colour-coded information, as well as visual discomfort while using red light.

3.4.6 Body temperature

There is evidence that high temperature can have a negative impact on the time course of dark adaptation (136-140). For example, Watanuki (29) measured dark adaptation time and threshold sensitivity in a climatic chamber. Initially, temperature and humidity were controlled at 29ºC and 50% (also referred to as thermo-neutral) while measures of dark adaptation were completed. Subsequently, temperature was reduced to 15ºC and the measurements repeated. Results show that the threshold sensitivity to light reached during 20 minutes of cooling (measured using tympanic membrane temperature) was significantly lower than during measurement at thermo-neutral temperature.

3.4.7 Daytime exposure to sunlight

Exposure to strong sunlight can produce a temporary but cumulative effect on dark adaptation. Studies have shown a significant decrease in performance of the rods after prolonged exposure to bright light (141-143). Around three hours of bright sunlight exposure has been shown to delay the onset of rod dark adaptation by 10 minutes or more and to increase the final threshold so that full night vision sensitivity could not be reached for hours (144). After 10 consecutive days of sunlight exposure, the losses in night vision were reported to cause a 50% loss in visual acuity, visibility range, and contrast discrimination in the dark (145). Repeated daily exposures to sunlight prolong the time to reach normal scotopic sensitivity, so that eventually normal rod sensitivity may not be reached (146).

4 ANALYSIS OF NIGHT TIME LOOKOUT DUTIES

4.1 MAINTAINING A SAFE NAVIGATIONAL WATCH

In order to understand what the dark adaptation implications are for the safe navigational watch, it is important to first understand the lookout duties undertaken by the bridge team at night. This was achieved by studying the appropriate maritime conventions, standards for Bridge Team duties and undertaking an analysis of the actual duties undertaken during the ship visits.

4.2 STATUTORY INSTRUMENTS

The International Maritime Organisation (IMO) has developed a wide range of international conventions aimed at the prevention of accidents, including standards for ship design, construction, equipment, operation and manning, search and rescue, the facilitation of international maritime traffic, load lines, the carriage of dangerous goods and tonnage, maritime security and the efficiency of shipping. The following conventions have been identified as those most relevant to maintaining a safe navigational watch, forming the basis of many standard operating procedures and ‘best practice’, and as such will be referred to throughout this report.

4.2.1 The International Convention for the Safety of Life at Sea, 1974 (SOLAS)

SOLAS covers various aspects of ship safety, including construction, fire protection, life-saving appliances, radio communications, safety of navigation, the carriage of cargoes and safety measures for high speed craft. Chapter V (Safety of Navigation) identifies certain navigation safety services that should be provided by governments that are signatories to the convention and sets forth provisions of an operational nature applicable in general to all ships on all voyages. The subjects covered include the maintenance of meteorological services for ships, the ice patrol service, routeing of ships, and the maintenance of search and rescue services. This chapter also includes a general obligation for Masters to proceed to the assistance of those in distress and for signatories to ensure that all ships shall be sufficiently and efficiently manned from a safety point of view.

4.2.2 The Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGS)

The Convention on the International Regulations for Preventing Collisions at Sea, 1972 sets out a "universal system of sea traffic rules" applicable to vessels in international waters. It includes 38 rules divided into five sections: Part A - General; Part B - Steering and Sailing; Part C - Lights and Shapes; Part D - Sound and Light signals; Part E - Exemptions and four Annexes containing technical requirements concerning lights and shapes and their positioning; sound signalling appliances, additional signals for fishing vessels when operating in close proximity and international distress signals.

4.2.3 The International Convention on Standards of Training, Certification and Watchkeeping 1978 (as amended) (STCW)

The Standards of Training Certification and Watchkeeping 1978 as amended (STCW 78), establishes basic principles to be observed in keeping a navigational watch, covering such matters as watch arrangements, fitness for duty, navigation, navigational equipment, navigational duties and responsibilities, the duties of the Lookout, navigation with a pilot onboard and protection of the marine environment. It establishes the minimum standards of training, certification and watchkeeping for seafarers at an international level and is complimented by the STCW Code, which contains recommended guidance and best practice examples that illustrate how to meet the requirements of STCW 78.

4.3 THE BRIDGE TEAM

All ship's personnel who have navigational watch duties are considered part of the bridge team. Regulations relevant to safe manning (Merchant Shipping (Hours of Work) Regulations 2002 and STCW 78) should be used to determine the number of qualified and experienced seafarers necessary to maintain the safety of the ship, crew, passengers, cargo and property and for the protection of the marine environment. To this end, owners and operators have a responsibility to ensure that the tasks, duties and responsibilities are sufficiently assessed and the number and grade of seafarers required to ensure safety of the ship are available at all times. Manning levels should be reviewed whenever changes in trading area(s), operations, construction, machinery, equipment and maintenance of the ship occur. The Bridge Procedures Guide (147) states that the navigational watch should comprise one (or more) qualified officers supported by appropriately qualified ratings[4]. The actual number of officers and ratings on watch at a particular time will depend on the prevailing circumstances and conditions. Duties should be clearly assigned, limited to those duties that can be performed effectively and clearly prioritised. At no time should the bridge be left unmanned without a qualified watchkeeping officer. Factors to be taken into account when composing a bridge watch include:

- Prevailing weather conditions and visibility;
- Proximity of navigational hazards which may make it necessary for the officer in charge of the watch to carry out additional navigational duties;
- The fitness for duty of any crew members on call who are assigned as a member of the watch, including compliance with applicable work hour regulations (Merchant Shipping (Hours of Work) Regulations, 2002);
- Use and operational condition of navigational aids;

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[4] Under certain circumstances a one man bridge operation is permissible, however under such circumstances support personnel should be readily and immediately available should assistance be required and there should be an established and continuously available means of communications for the watch keeper to summon such assistance. However, this should never be the case at night, or under conditions of poor visibility (147).

- The experience of each OOW, and the familiarity of that Officer of the Watch with the ship's equipment, procedures and manoeuvring capability;
- Whether the vessel is fitted with automatic steering;
- Whether there are radio duties to be performed;
- Special operational circumstances; and
- The availability of assistance should prevailing conditions change.

The basic tenet of Bridge Team Management (BTM) is to make the most effective use of available manpower while at the same time maintaining a watch size and structure that is appropriate to expected operating conditions (i.e. restricted waterways, traffic concentrations, and restricted visibility). It effectively addresses the primary functions of the bridge (i.e. navigation, collision avoidance, and communication) and has clearly defined roles and responsibilities for each bridge team member. With regards to lookout duties, this includes both the OOW and the Lookout.

4.3.1 Voyage Planning

The ability to maintain a safe navigational watch is itself part of a higher order activity: voyage planning. The development of a voyage plan, as well as the close and continuous monitoring of the vessel's progress and position during the execution of such a plan, is essential for the safe and efficient conduct of vessels at sea. Prior to departure the navigator (in conjunction with the Master) should prepare a full 'berth to berth' voyage plan that provides detailed operational information for the whole voyage, which should include the following factors:

- The intended route or track of the voyage including areas of danger, ships' routeing and reporting systems and vessel traffic services.

- Safe speed, including any speed alterations en route due to navigational hazards along the intended route or limitations because of night passage, tidal restrictions, or allowance for the increase of draught due to squat and heel effect when turning.

- The minimum clearance required under the keel in critical areas with restricted water depth.

- Way-points: used to indicate important time line events as well as when to alter course, taking into account the vessel's turning circle at the planned speed and any expected effect of tidal streams and currents.

- The method and frequency of position fixing including areas where accuracy of position fixing is critical.

- Considerations relating to the protection of the marine environment.

Contingency plans for alternative action to place the vessel in deep water or proceed to a port of refuge or safe anchorage in the event of any emergency necessitating abandonment of the plan, taking into account existing shore-based emergency response arrangements and equipment and the nature of the cargo and of the emergency itself.

4.3.2 The Role of the Officer of the Watch (OOW)

The primary role of the OOW is to ensure that the voyage plan is executed. The voyage plan should always be available on the bridge and during the voyage, the OOW should make significant reference to the voyage plan acknowledging way points and updating the notes section of the plan as actions are completed or changes required. The OOW has operational responsibility for the ship during their watch shift (the Master retains overall command of the ship and responsibility for its safety at all times). The OOW is the Master's representative and is responsible at all times for the safe navigation of the ship, and for complying with the COLREGS. It is the responsibility of the OOW to ensure that a proper lookout is maintained.

Traditionally, the primary focus of the OOW would have been identifying and responding to the risk of collision, stranding, the presence of ships in distress and other hazards to safe navigation. However, the contemporary bridge environment, where automated systems perform many of these functions, is far more complex. Consequently, the role of the OOW as a direct controller has been fundamentally changed into that of a supervisor and decision maker (148). The OOW is required to maintain a continuous state of situational awareness, with regard to significant changes in the operating environment, which includes keeping lookout when operational demands are low.

Much of the task of maintaining a safe navigational watch is characterised by activities involving basic control of the vessel, such as maintaining appropriate speed, course and position. The OOW will need to be familiar with methods of controlling the speed and direction of the ship, handling characteristics and stopping distances. However, the key component of maintaining a safe navigational watch is to avoid collision by identifying ships, navigation marks, floating debris and other potential dangers to navigation that may cross the ship’s path. Watch officers are required to process navigation information from several different sources including Radar, AIS, compass, ECDIS, VTS, GMDSS, etc, in order to determine if the ship’s present course is safe. They are then required to calculate the ship’s future position and plan for future contingencies. The safety and efficiency of the ship can depend on the alertness and effectiveness of the Lookout. This is particularly true in high traffic density areas where high numbers of fishing vessels and small leisure/recreational craft may be present in addition to larger obstacles. The movement of small vessels is unpredictable as they do not generally follow set routes and timetables and such vessels are generally not required to report their movements to the VTS and may not be detected by radar systems (149).

It is important that a proper, formal record is kept of navigational activities and incidents, which are of importance to safety of navigation. It is the responsibility of the OOW to compile such records as part of their watch duties. The deck log is a complete daily record, by watch, of every significant occurrence regarding the operation and safety of the ship. The deck log typically records the time (24 hour notation) of significant events, such as getting underway, passing charted landmarks and waypoints, and when the ship reaches its destination. In addition to the deck log some vessels (as with the RoPax vessels) may also complete a weather log and a Marine Operations Abstract (MOA).

4.3.2.1 Handing over

An important stage of the navigational watch, particularly in terms of dark adaptation, is the handing over of the watch to the next shift. As part of the handover process the outgoing OOW should:

- Ensure that the members of the relieving watch are fully capable of performing their duties;
- Ensure that the vision of the relieving watch is fully adjusted to the light conditions;
- Ensure that all standing orders and the Master’s night orders are fully understood.

The OOW should not hand over the watch if there is reason to believe that the relieving officer is not capable of carrying out the watchkeeping duties effectively. They should ensure that the relieving officer has received all relevant instructions and information that will ensure the continued safe conduct of the vessel. Prior to taking over the watch, the relieving officer should:

- Verify the vessel's estimated or true position;
- Confirm the vessel's intended track, course and speed;
- Note any dangers to navigation expected to be encountered during the watch;
- Be aware of prevailing and predicted tides, currents, weather, visibility and the effect of these factors upon course and speed;
- Note any errors in gyro and magnetic compasses;
- Note the status of all bridge equipment;
- Note the settings of bridge/engine controls and manning of engine room;
- Be aware of the presence and movement of vessels in sight or known to be in the vicinity.

4.3.3 The Role of the Lookout

The role of the Lookout is to support the OOW by keeping lookout for other ships (especially those in distress), navigation marks, floating debris and other potential dangers to navigation that may cross the ship’s path. Traditionally, the Lookout would have been the primary method of identifying such hazards however, with the introduction of Radar, Automatic Radar Plotting Aids (ARPA), Vessel Traffic Services (VTS), etc, the Lookout has become a back up to these systems. Nevertheless, reliability issues, such as interference and display clutter, mean that the safety and efficiency of the ship still depends on the alertness and effectiveness of Lookouts, as the Lookout may be the first to observe possible hazards. Other duties that may traditionally be performed as part of the bridge team include acting as a helmsman and carrying out deck, accommodation and fire and safety patrols. In addition to traditional deck duties, ratings onboard the RoPax vessels were required to assist with berthing, cargo operations (i.e. arranging trestles to support unaccompanied lorry trailers and lashing all vehicles for the passage), and un-berthing. However, the Lookout should give their full attention to watchkeeping and no extraneous duties should be performed that could interfere with that task. In turn, the OOW should consider Lookouts as an integral part of the bridge team and utilise them to the fullest extent, keeping them apprised of the current navigational situation.

4.4 ANALYSIS OF OBSERVED BRIDGE TEAM DUTIES

This was achieved using an approach called hierarchical task analysis (HTA). The task analysis sought to determine what the demands on the bridge team are and also what other factors are present that could influence the team's performance in relation to lookout duties at night. The first step in analysing a task is to identify and focus upon the main goal of the analysis (150). In this instance the desired system goal is 'maintaining a safe navigational watch'. Data collected from the observation of night time duties on the bridge and information from informal interviews, conducted with members of the bridge crew, were used to identify the activities associated with maintaining a safe navigational watch. Figure 11 displays a HTA of the bridge team during the navigational watch. It shows many of the routine tasks that the crew must perform to maintain a safe navigational watch. It is not inclusive of every task a member of the watch may perform. During the site visits it was not possible to collect data relating to infrequent events, such as general maintenance tasks, fire and safety drills, activities during adverse weather conditions or system failures, etc. The main activities observed during the ship visits were:

- The OOW checking the vessel's position, course and speed using the ships navigational aids to ensure that the vessel was following the planned track, as detailed in the voyage plan and received orders (Figure 11, Task 1.1);
- The OOW/Lookout monitoring radio-communications and environmental conditions for threats to the safe conduct of the craft (Figure 11, Task 1.2);
- The OOW maintaining the deck log/MOA in order to keep a record of the movement of the vessel in relation to the voyage plan (Figure 11, Task 1.3); and
- The Lookout keeping a visual watch for other ships, navigation marks, floating debris and other potential dangers to navigation that may cross the ship's path (Figure 11, Task 1.4).

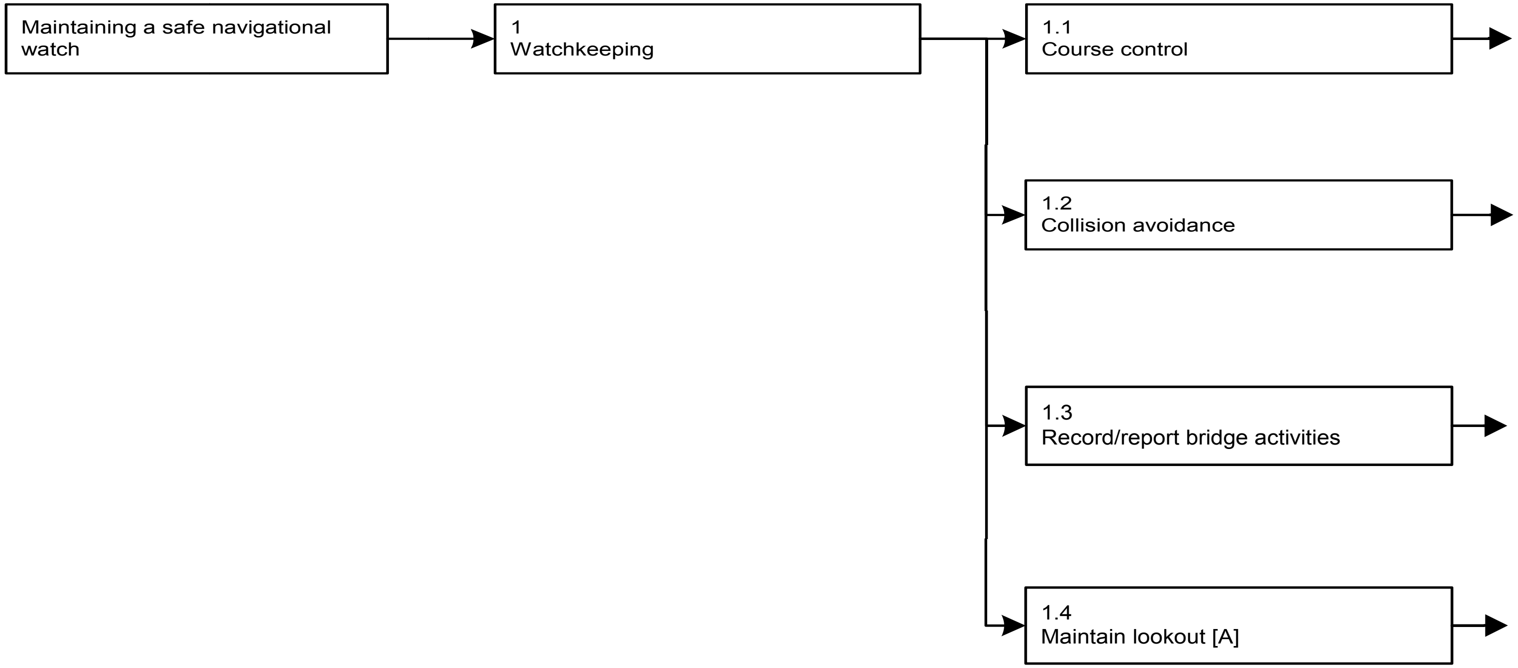


Figure 11a Hierarchical Task Analysis of maintaining a safe navigational watch: Top Level

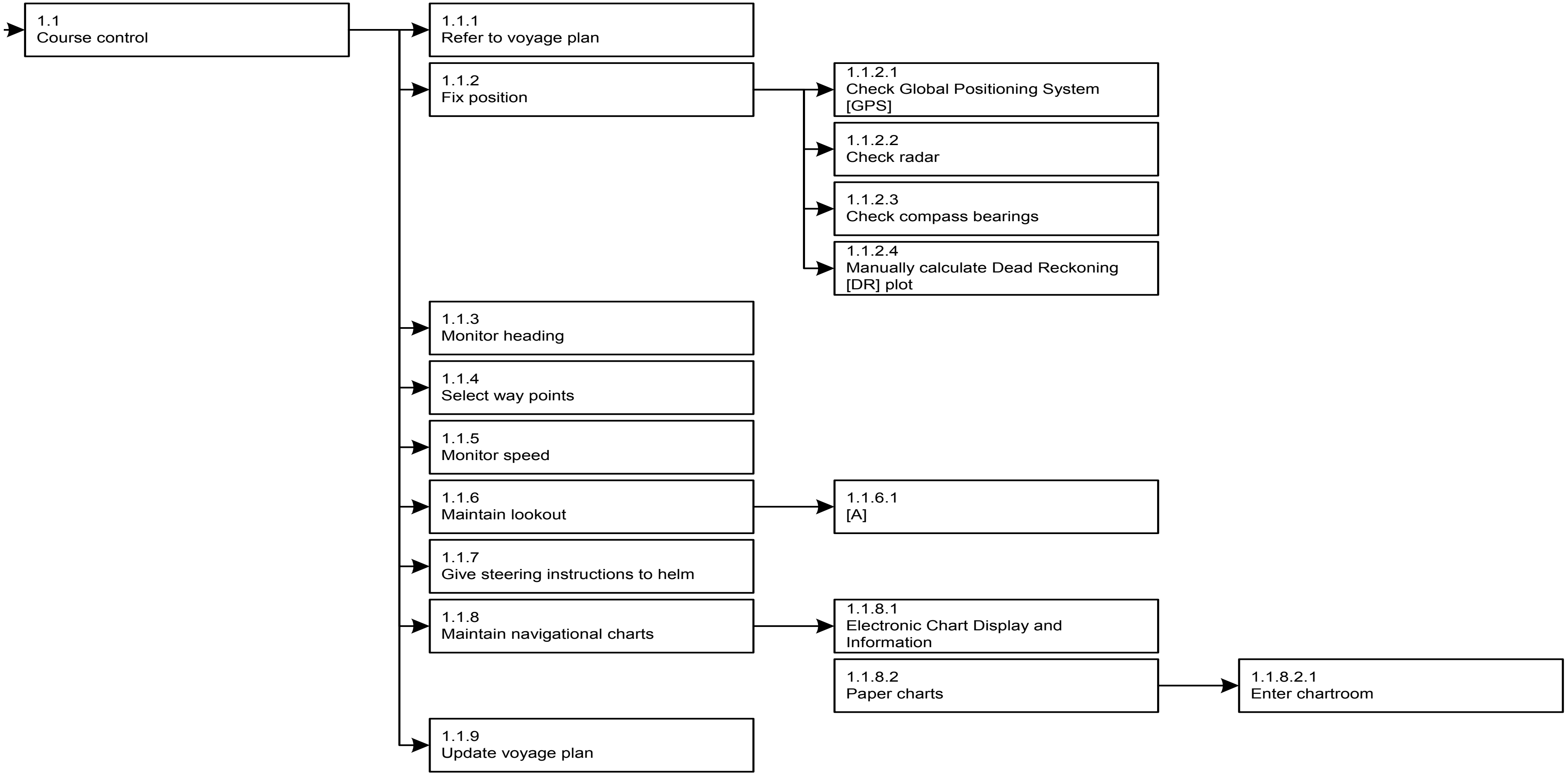


Figure 11b Hierarchical Task Analysis of maintaining a safe navigational watch: Level 1.1

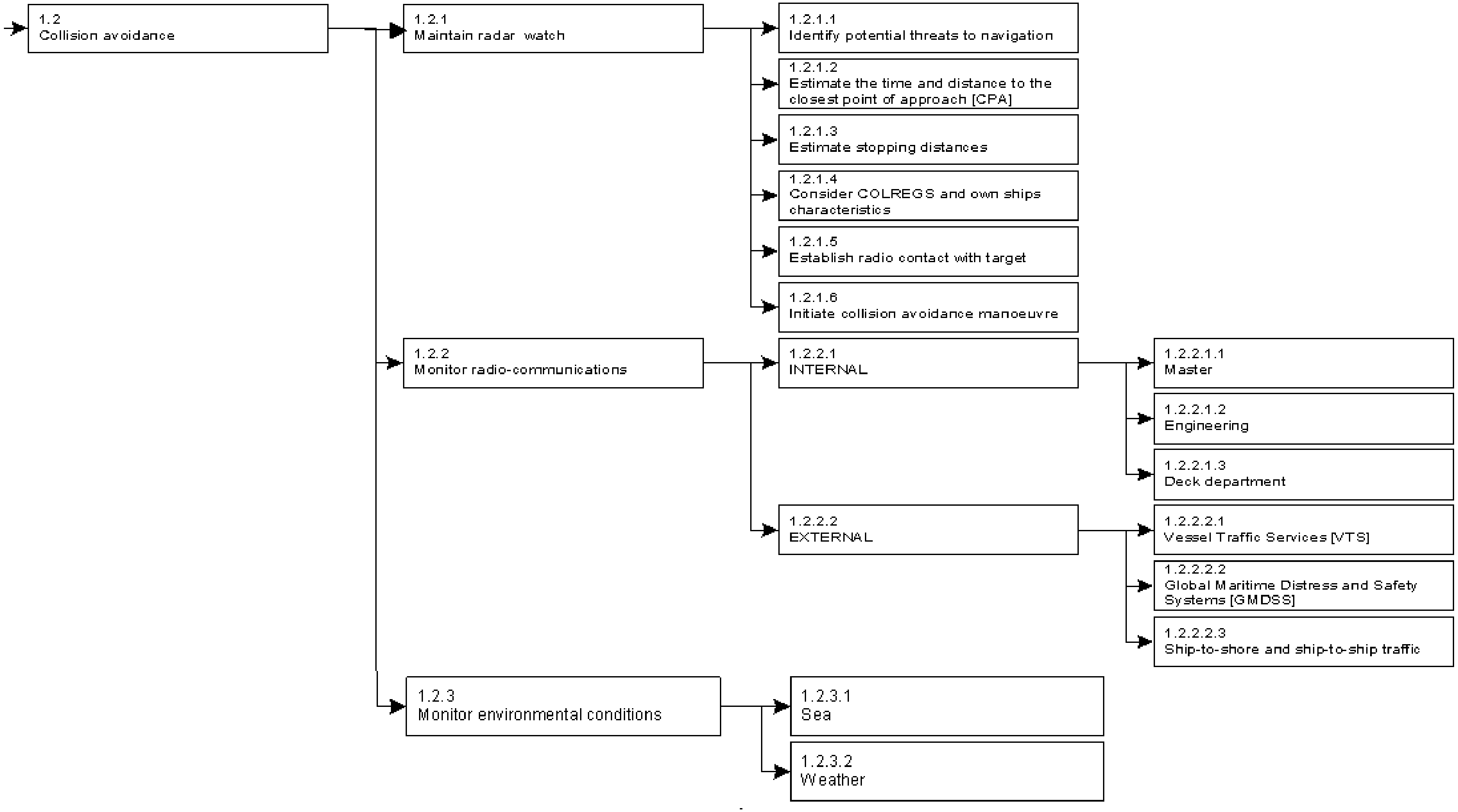


Figure 11c Hierarchical Task Analysis of maintaining a safe navigational watch: Level 1.2

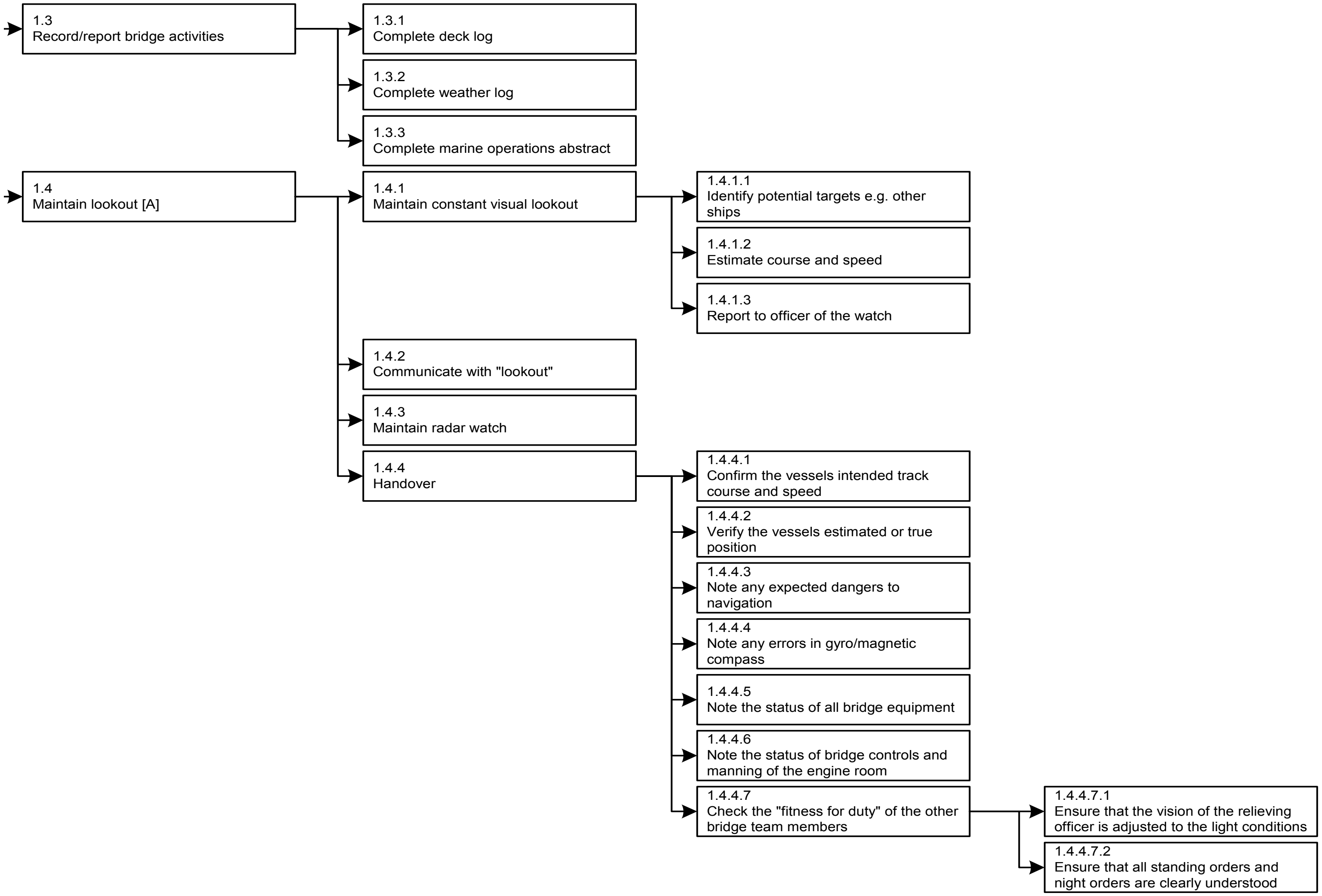


Figure 11d Hierarchical Task Analysis of maintaining a safe navigational watch: Levels 1.3 and 1.4

Summary

The lookout task is primarily a visual search task that involves the active scanning of the visual environment for the navigational lights of other ships (119), which is, in the first instance, a detection task. The role of the Lookout is to support the OOW by keeping lookout for other ships (especially those in distress), navigation marks, floating debris and other potential dangers to navigation that may cross the ship's path. Other duties that may be performed as part of the bridge team include acting as a helmsman and carrying out deck, accommodation and fire and safety patrols. The main activities of the navigational watch are:

- Checking the vessel's position, course and speed using all appropriate navigational aids and means necessary to ensure that the vessel follows the planned track, as detailed in the voyage plan and received orders;
- Detecting dangers to navigation occurring in the ship's surface and subsurface environments, and counteracting them in a timely and proper manner;
- Keeping a proper record during the watch of the movement of the vessel and activities relating to the navigation of the vessel.

An important stage of the navigational watch, particularly in terms of dark adaptation, is the handing over of the watch to the next shift, where the OOW must:

- Ensure that the members of the relieving watch are fully capable of performing their duties;
- Ensure that the vision of the relieving watch is fully adjusted to the light conditions;
- Ensure that all standing orders and the Master's night orders are fully understood.

It is essential that all seafarers over the age of 18 meet basic visual acuity and colour vision standards. These standards are based on photopic visual acuity. Under scotopic conditions, the luminance contrast sensitivity of a target quantifies its visibility relative to its immediate background. Objects can be seen at night only if they are either lighter or darker than their background and can be discriminated by subtle differences in contrast. The lookout task at night is predominantly reliant on positive contrast (when a bright object lies on a dark background), as the Lookout must identify the relatively bright navigational lights of other ships against the dark background of the night sky or the sea. Evidence suggests that scotopic retinal threshold may be the most appropriate parameter for evaluation and prediction of night vision capability in the field during moonless nights, while mesopic contrast sensitivity is a more reliable parameter when the moon is half full.

5 ASSESSMENT OF THE BRIDGE LIGHTING ONBOARD THE SHIPS

An assessment was conducted to determine the amount of light bridge operators are exposed to under normal operating conditions including, naturally occurring light e.g. moonlight and any light emitted from onboard equipment, that contribute to ambient light levels on the bridge. During the site visits it was observed that the strength of the moonlight made a significant contribution to the ambient light levels on the bridge, influencing the dark adaptation of the lookout, which may also affect the contrast between target objects and the background (i.e. the night time environment), making objects more difficult to detect. Adaptation to light occurs when exposed to a light source, even briefly; therefore the main purpose of the lighting survey is to identify significant sources of light that the OOW and Lookout may be exposed to within the operational bridge environment.

5.1 ROPAX BRIDGE ASSESSMENT

5.1.1 Illuminance: Bridge

Measurements of illuminance, the amount of light falling on the horizontal meridian, were taken on every workstation on the bridge. At each measurement site a measure of the horizontal illuminance was taken at desk height using a calibrated Minolta T1 illuminance meter (SN 207621). The measurements are indicated on the sketch plan in Figure 12. The average illuminance on the bridge was 0.15 lux; the minimum illuminance value measured in the area was 0.02 lux. Measurements were made on the 9th and 10th of December 2009, while the moon phase was last quarter (◑). Spot measurements were made of broadly representative conditions in the corridors and cabins adjacent to the bridge. The average illuminance in the cabins was 165 lux. The average illuminance in the corridor adjacent to the bridge was 82.6 lux.

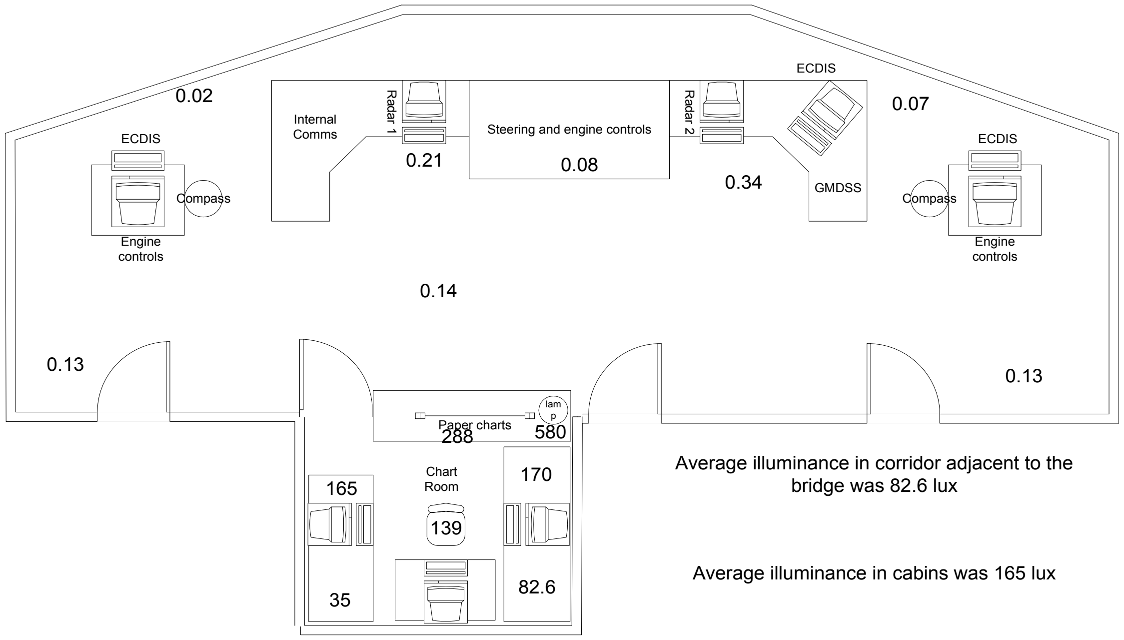


Figure 12 Sketch showing the general layout of the RoPax bridge and the location of measuring points. Illuminance values are shown in lux (not to scale)

5.1.2 Illuminance: Chartroom

The chartroom onboard the RoPax vessel was located at the rear of the bridge and was fitted with a window, so that during the day the OOW could access the information in the chartroom without leaving the bridge. However, this is impractical at night, as the light from the chartroom would flood the bridge causing adaptation to occur; therefore ‘blackout’ curtains were used to shield the bridge from light within the chartroom. Due to the presence of electronic charting on the bridge, visits to the chart room were infrequent. The OOW entered the chartroom occasionally to manually check the ship’s position relative to the passage plan, and to update the deck log.

The chartroom had a discharge lamp (fluorescent strip light), which was turned off during the voyage so was not measured, and one lamp fitted with a 60W incandescent bulb, kept on during the voyage, which was located to the side of the chart. The illuminance levels beneath the lamp were the highest (288 lux). In the centre of the chart table the levels were lower (139 lux). The average of all the illuminance measurements taken in the chartroom was 146.6 lux; the minimum illuminance value measured in the area was 35 lux. The measurements are indicated on the sketch plan in Figure 12.

5.1.3 Luminance: Bridge

Measurements of luminance, the amount of light reflected or emitted from a surface, were taken from the key workstations within the operator’s field of view. Measurements were taken using a calibrated Minolta LS110 Luminance Meter (SN71323008). In use, the luminance meter is aimed like a camera, and can be focused upon the target using its optical zoom lens. The meter uses a ‘through the lens' viewing system, so the observer views what the photocell will measure when activated. The luminance meter has a 1/3° (narrow) acceptance angle, which means that it can be accurately focused on a particular target or portion of a target. The optical system of the meter is also designed so that the photocell is unaffected by light sources outside the focused measurement area. Luminance measurements were taken from the operator's standing position in front of the equipment controls.

Table 4 Luminance measures of the key workstations on the RoPax Bridge

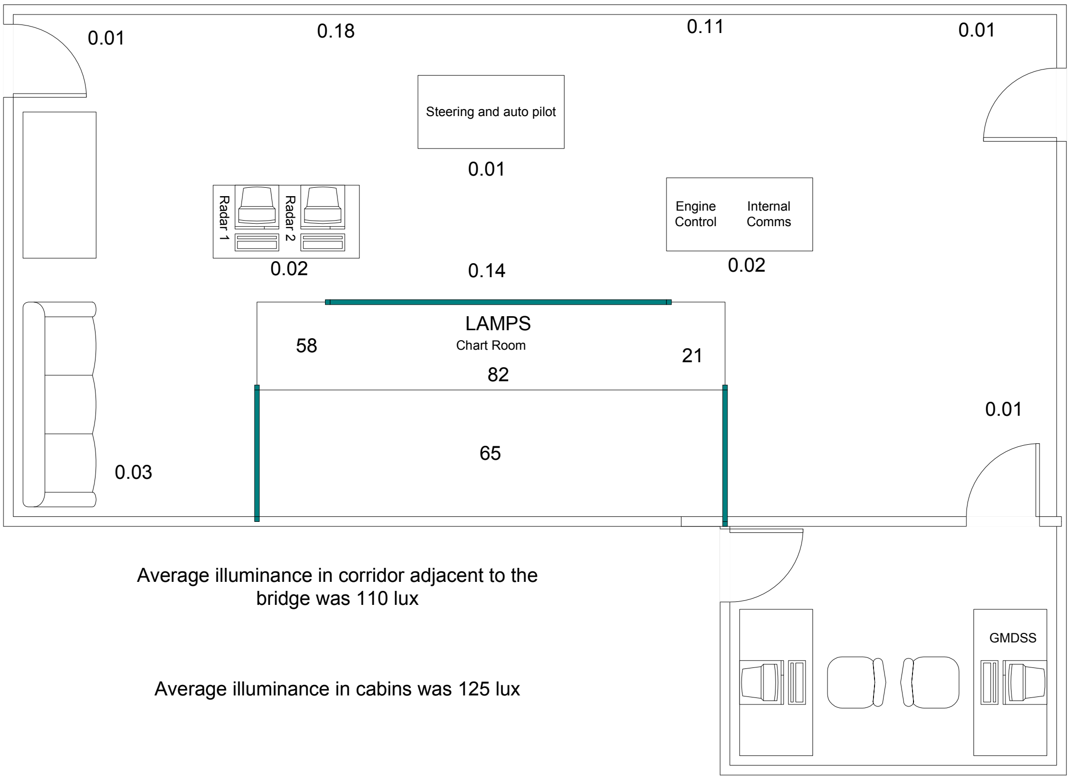
Target	**Luminance (cd/m^2)**
ECDIS	5.8
Radar 1: Background	0.1
Radar 1: Output	0.72
Radar 2: Background	0.16
Radar 2: Output	0.21
Engine controls	2.4
NAVTEX (LCD blue display)	0.56

Table 4 indicates that most of the measured luminances were very low, which is a direct effect of the low ambient lighting on the bridge and the night time settings applied to the equipment displays.

5.2 TANKER BRIDGE ASSESSMENT

5.2.1 Illuminance: Bridge

Measurements of illuminance, the amount of light falling on a horizontal surface, were taken on every workstation on the bridge. At each measurement site a measure of the horizontal illuminance was taken at desk height using a calibrated Minolta T1 illuminance meter (SN 207621). The measurements are indicated on the sketch plan in Figure 13. The average illuminance on the bridge was 0.05 lux; the minimum illuminance value measured in the area was 0.01 lux. Measurements were made on the 24th January 2010, while the moon phase was first quarter (◐). Spot measurements were made of broadly representative conditions in the corridors and cabins adjacent to the bridge. The average illuminance in the cabins was 125 lux. The average illuminance in the corridor adjacent to the bridge was 110 lux.



Average illuminance in corridor adjacent to the bridge was 110 lux

Average illuminance in cabins was 125 lux

Figure 13 Sketch showing the general layout of the Tanker bridge and the location of measuring points. Illuminance values are shown in lux (not to scale)

5.2.2 Illuminance: Chartroom

The chartroom onboard the tanker was integral to the bridge. During the day, the chartroom was an open sided workstation, effectively a desk in the middle of the bridge. At night ‘blackout’ curtains were used to cordon off the chartroom area creating a separate room within the bridge. The tanker operated with traditional paper charts, which meant that visits to the chart room were more frequent than on either of the RoPax vessels. In addition to the ship's charts, navigational aids such as radio direction finders, global positioning system and a Loran-C positioning systems were located in the chartroom. The OOW frequently entered the chartroom to manually check the ship’s position relative to the passage plan, and to update the deck log.

The chartroom had two table lamps, both fitted with 40W incandescent bulbs that were kept on during the voyage. The illuminance levels beneath the lamps were the highest (82 lux). In the centre of the chartroom the levels were lower (65 lux). The average of all the illuminance measurements taken in the chartroom was 56.5 lux; the minimum illuminance value measured in the area was 21 lux. The measurements are indicated on the sketch plan in Figure 13.

5.2.3 Luminance: Bridge

Measurements of luminance were taken from the key workstations on the bridge. Measurements were taken using a calibrated Minolta LS110 Luminance

Meter (SN71323008). Luminance measurements were taken from a standing position adjacent to the equipment controls as before.

Table 5 Luminance measures of the key workstations on the Tanker Bridge

Target	Luminance (cd/m^2)
Radar 1: Background	0.01
Radar 1: Output	1.37
Radar 2: Background	0.01
Radar 2: Output	1.15
Engine controls	0.14
Internal communications	0.25

Table 5 indicates that most of the measured luminances were very low, which is a direct effect of the low ambient lighting on the bridge and the night time settings applied to the equipment displays.

5.3 SPATIAL LINK ANALYSIS

A spatial link analysis was conducted in order to examine the movement of the bridge team during night time navigation and, in particular, the frequency of visits to the chartroom. Four random samples (two from each leg of the journey) of 30 minutes were taken from the footage recorded during the RoPax ship visits and two samples were taken from each night of the tanker visit (total of four). Figure 14 illustrates the topographical relationship between the bridge crew, other system components (i.e. items of equipment on the bridge) and different areas of the bridge (represented alphabetically). This considers only the basic physical relationships between system components; every time two items are linked a line is drawn between them, thus the more frequently two components are linked, the greater number of lines are drawn between them. This is useful for identifying what equipment and which areas of the bridge are used most frequently by the different members of the bridge team. These diagrams do not represent the sequence of interactions as many of the activities do not occur in serial and involve parallel processing of information. Figure 15 shows the movement of the tanker bridge team during 30 minutes of observation.

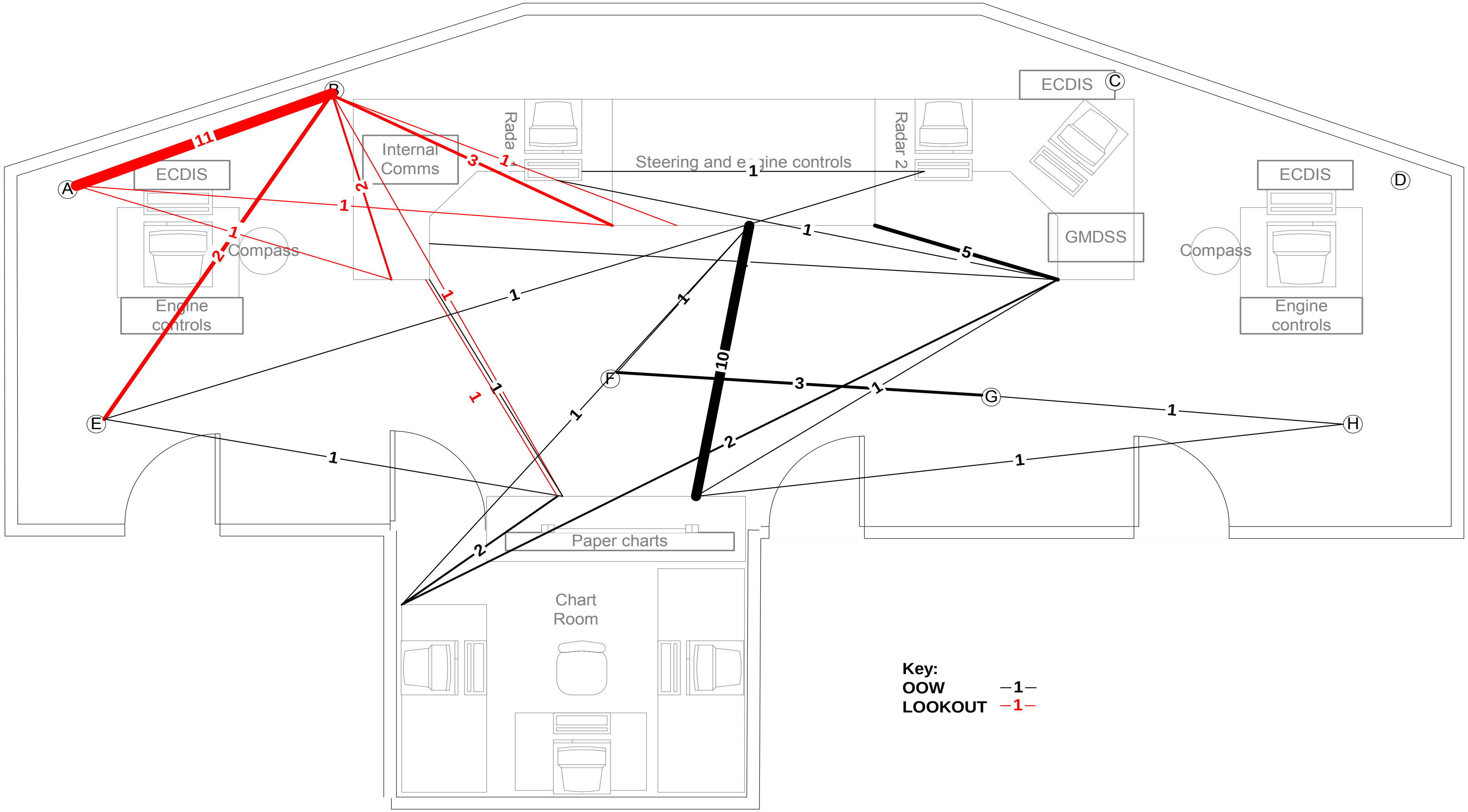


Figure 14 Movement of the RoPax bridge team during 30 minutes of observation

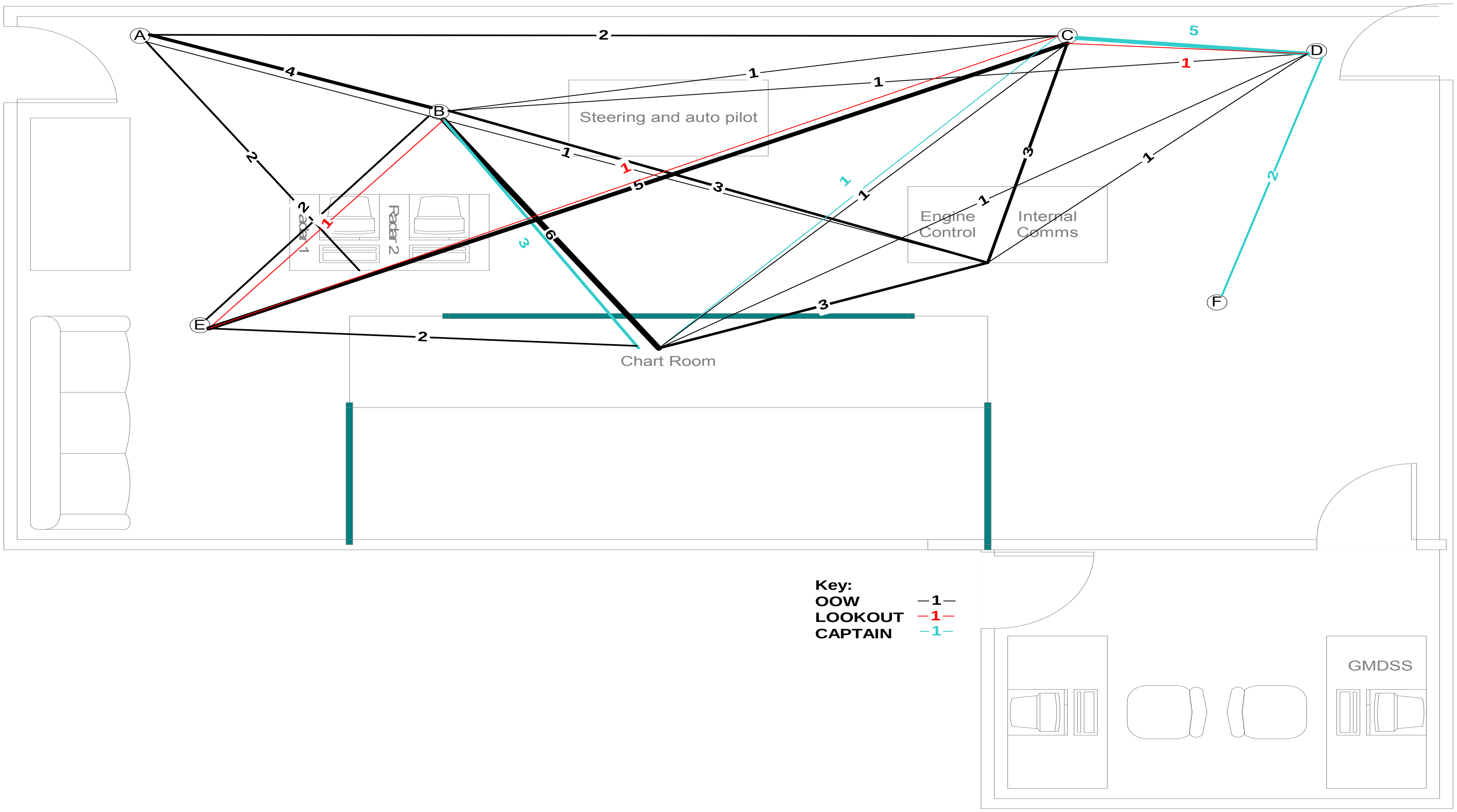


Figure 15 Movement of the Tanker bridge team during 30 minutes of observation

6 ASSESSMENT OF DARK ADAPTATION ONBOARD THE SHIPS

6.1 THE DARK ADAPTATION CURVE

The classic Dark Adaptation Curve (DAC) reported by Hecht and Mandlebaum (18), which was provided in Figure 3 (Section 3.1.2), shows a biphasic, nonlinear decrease in visual threshold with time after initial pre-adaptation to a very bright light source. The first phase of the curve reflects cone receptor function and takes around 5 to 10 minutes to complete, approaching a minimum threshold in the mesopic range (12). After this time the rod-cone break occurs; the sensitivity of the rod pathway improves to the point where the rods begin to function better than the cones (21). The rods require around 30 to 45 minutes to effectively reach their minimum (absolute threshold) of around 10^{-5} cd/m^2 (12). However, it is highly unlikely that the bridge crew will, prior to commencing night time lookout duties, be exposed to light levels that are comparable to those used in the laboratory study of dark adaptation (151).They are far more likely to adapt from much lower levels of light e.g. cabin or corridor light levels and decreasing the light levels prior to adaptation reduces the initial threshold of detection and decreases the time taken to reach both the rod-cone break, and the minimum detection threshold achieved (31).

A further difficulty in trying to extrapolate from laboratory studies of dark adaptation to the context of the ship's bridge is that, in the former case, after bleaching, the person is put into a totally dark environment, whereas the bridge is not in complete darkness. A key factor in determining the ambient light level on the bridge is the level of moonlight, which will vary depending on the phase of the moon, influencing the dark adaptation of the Lookout. This may also affect the contrast between target objects and the background (i.e. the night time environment), making objects more difficult to detect. Where no moon is present it may be possible that the bridge team will operate in near total darkness (scotopic vision). However, the average illuminance on the RoPax bridge was 0.15 lux, while the average illuminance on the tanker bridge was 0.05 lux, which suggests that mesopic, rather than scotopic, vision may be of primary importance on the bridge because some light is often present during night operations (146). There is a common misconception that only the rods are used at night and only the cones are used during the day. Actually, both rods and cones function over a wide range of light intensity levels and at intermediate (mesopic) levels of illumination, they function simultaneously (Figure 2). Neither the rods nor the cones operate at peak efficiency in this range, but both actively contribute to visual perception (152).

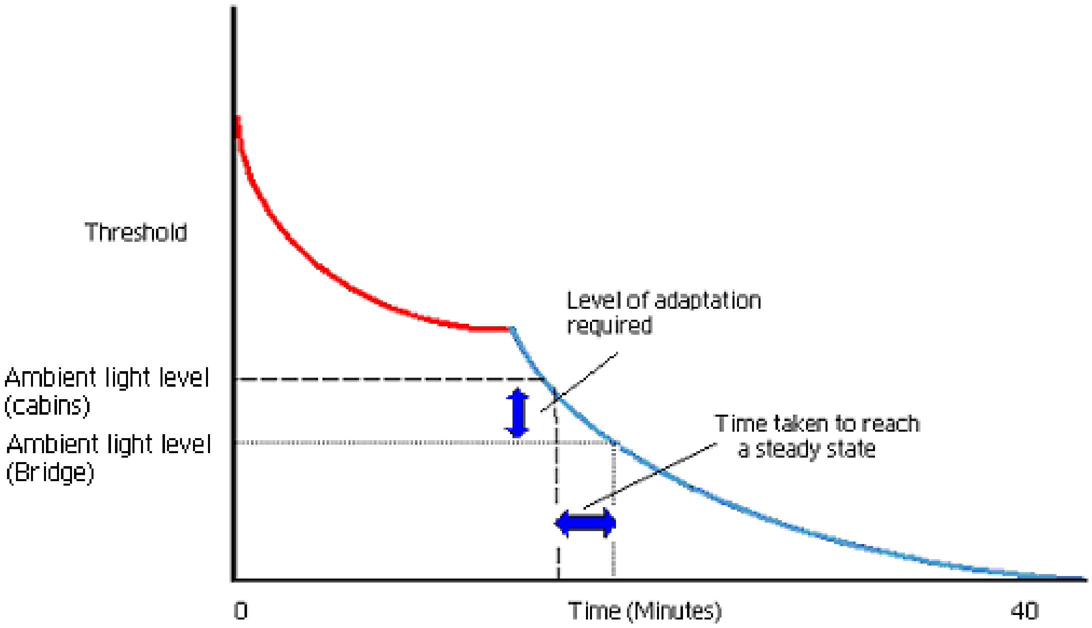


Figure 16 Graphical representation of the level of dark adaptation required on the Bridge at night

Figure 16 represents the typical dark adaptation curve with the effects of a lower initial light level (the pre-adapted state) and a higher steady state post adaptation level (i.e. not total darkness). The coloured curve is the threshold for the eye, the minimum amount of light needed to detect the light. The colours in the figure are used for illustration - the red portion being determined by the cones, the blue portion by the rods. In this instance, the dashed line (---) represents the hypothetical threshold value when the eye has been adapted to a much lower light level (e.g. under the lights in a cabin), and the dotted line (…) represents the hypothetical threshold value when the eye is in a low-illuminance environment (e.g. a ship's bridge). The difference between the two vertical lines is an approximation of the time taken for the Lookout to reach their steady state and is the minimum time needed before handover should occur.

It is necessary to conduct further research to accurately define the amount of time required to dark adapt under the conditions observed onboard, and to determine whether the time taken to adapt and the threshold achieved varies with age and refractive error. In a normal environment at any point in time, the sensitivity of the eye is determined by the ambient conditions. If you increase the ambient light level the eye light adapts by that amount, and if you decrease the ambient light level the eye dark adapts by that amount. Raising the adaptation level is quick, but lowering it is much slower. What is relevant for the time needed for the Lookout to be on the bridge is the time taken to go from the adaptation state they are in prior to being on the bridge, to that when on the bridge (as indicated by the horizontal lines in Figure 16).

6.2 TIMINGS OF HANDOVERS OBSERVED

A key factor in the impact of dark adaptation is the amount of time spent adjusting to dark conditions. Current legislation (STCW 78) states, with respect to dark adaptation:

"The relieving officer shall ensure that the members of the relieving watch are fully capable of performing their duties, particularly as regards their adjustment to night vision. Relieving officers shall not take over the watch until their vision is fully adjusted to the light conditions".

However these regulations fail to specify a time period that is sufficient for "complete" (effective) dark adaptation to occur, or to recognise the range of night time light levels to which Lookouts will need to become adapted to in practice. The IMO (153) has defined the suitable period for dark adaptation to be typically, 10 to 15 minutes and indicates that the same period of dark adaptation will be required every time the lookout returns to the bridge. This is supported in the fourth edition of the Bridge Procedures Guide (147), which states that "full" night vision will not be achieved in less than 15 minutes. The current results support this time frame. Table 6 shows the time period of each night time handover observed during the ship visits. The RoPax vessels operated a 6-hour watch pattern; watch changes occurred at 24:00 hours, shortly after the vessel had cleared the port, and 06:00, just prior to arriving at the destination port. The tanker operated the more traditional four-hour watch pattern, watch changes occurred at 20:00, 24:00 and 04:00. In terms of the guidance currently available, only one of the handovers observed met the stated 15 minute criteria and the average length of handover on both the RoPax and tanker failed to meet this limit. Furthermore, only 50% of the handovers observed met the criteria of 10 minutes defined in IMO MSC.1/Circ.1280.

Table 6 Length of handover time (minutes)

	20:00	24:00	04:00/06:00	Average
RoPax				
Night 1		10.51	4.48	7.49
Night 2		3.02	21.27	12.30
Tanker				
Night 1	10.39	7.58	12.01	10.13
Night 2	6.14	8.1	11.51	8.45

6.3 THE IMPACT OF THE CHARTROOM ON DARK ADAPTATION

During normal bridge operations, the need to enter the chartroom is considered to be the most significant factor affecting dark adaptation (as shown by the spatial link analysis). The average illuminance in the RoPax chartroom was 146.6 lux, while the average illuminance in the tanker chartroom was 56.5 lux. The IMO Guidelines on ergonomics requirements for bridge layout (IMO (154) MSC/Circ.982) state that "A satisfactory level of lighting should be available to enable bridge personnel to complete such tasks as maintenance, chart and office work satisfactorily, both at sea and in port, daytime and night time." Furthermore, the lighting required on the bridge should be designed so as not to impair the night vision of either the OOW or the Lookout.

All information should be presented emitting as little light as possible at night, and red or filtered white light (i.e. a white lamp with a red filter attached) should be used to maintain dark adaptation whenever possible. Adjustable lighting (dimming control) should be provided for controls and visual displays, including display, control and panel labels and critical markings, which must be read at night or under darkened conditions. The range of the dimming control should permit the displays to be legible under all ambient illumination conditions. Table 7 lists the recommended illuminance levels stated in IMO MSC/Circ.982.

Table 7 Recommended illuminance levels stated in IMO MSC/Circ.982

Place	Colour/Illumination
Bridge, night	Red or filtered white, continuously variable from 0 to 20 lux
Adjacent corridors and rooms, night	Red or filtered white, continuously variable from 0 to 20 lux
Chart table, night	Filtered white floodlight or spotlights, continuously variable from 0 to 20 lux

In general, the illuminance levels on the bridge were below those recommended in IMO MSC/Circ.982. However, the illuminance readings in the chartroom were significantly higher than recommended and, for a short time, would cause the eye to readapt to light, even if exposure to the light was brief. This suggests that the number and duration of visits to the chartroom may be a significant issue in terms of dark adaptation. However, this effect may be mediated by the fact that the lookout remained on the bridge while the OOW was in the chartroom, meaning that at least one member of the bridge team was adapted to the ambient conditions at all times during the watch.

The bridge teams on the RoPax vessels made far fewer visits to the chartroom (approximately 5 per sample) in comparison to the bridge team on the tanker (approximately 12 visits per sample). Furthermore, when the same sample footage was used to calculate both total and average time spent in the chartroom, results indicate that the duration of visits was far greater for the tanker bridge crew (an average of 2 minutes 17 seconds per visit) than the bridge crews on the RoPax vessels (an average of 1 minute 29 seconds per visit). The longest time period spent in the chartroom, during observation on the RoPax vessels, was 3 minutes and 58 seconds, compared to 13 minutes and 52 seconds on the oil tanker.

Table 8 shows the total amount of time spent in the chartroom during the four 30-minute sample observation periods. Note that the tanker operated a three-man bridge team and it was the junior officer that made visits to the chartroom, not the OOW. One possible explanation for the differences observed is that the RoPax vessels were fitted with ECDIS as part of the integrated bridge system, reducing the need to refer to papers charts and in turn the need to enter the chartroom.

Table 8 Total time (minutes) spent in the chartroom during 30 minutes of observation

	Night 1		**Night 2**	
	1	**2**	**3**	**4**
RoPax	4.24	13.55	8.55	1.09
Tanker	20.19	27.53	16.20	27.48

7 CRITICAL FACTORS FOR BRIDGE TEAM DARK ADAPTATION

7.1 VISUAL SEARCH

The lookout task is primarily a visual search task that involves the active scanning of the visual environment for the navigational lights of other ships, which may appear as no more than specks of light on the horizon (119). This is essentially a threshold contrast-detection task. Physical factors relating to the stimulus variable such as target size and context, illumination, light wavelength, contrast, exposure or viewing time, distances to target and relative angular velocity of the target (with respect to the viewer) are an important element of successful visual search (12). However, the lookout task at night is predominantly reliant on positive contrast (when a bright object lies on a dark background), as the Lookout must identify the relatively bright navigational lights of other ships against the dark background of the night sky or the sea. Figure 17 illustrates the factors which affect the probability detecting of a spot of light at night, including:

- The luminance of the light, as seen from the Lookout's position;
- The luminance of the surround, as together these provide the contrast, i.e. the luminance of the lamp has to be higher than the luminance of the surround in order for the light to be detected; and
- The adaptation state of the eye, which will be determined by the ambient conditions and pre-adaptation exposure to light. It is important to recognise that the lookout will not be staring into a totally black space. The moon and stars will illuminate the sea, and although the luminance will be low it will still be noticeably above absolute threshold.

The distribution of rods and cones across the surface of the retina (Figure 1) has important consequences for visual performance (155). People see the *details* of objects much less well when they are not fixated directly, i.e. when the object is off the direct line of sight, as the eye has lower peripheral acuity and visual attention is usually concentrated where the viewer fixates i.e. directly ahead (56). When one turns one's eye to 'look at' something, the action places the image onto the fovea, which is the portion of the retina with the best visual acuity. The high acuity comes about because the fovea contains only cones, and is completely devoid of rods. As a consequence, if the luminance of a small object is below cone threshold, it cannot be seen if it is fixated, and at low light levels a comparative 'blind spot' exists in the central 1 degree of the visual field. This is a crucial factor in the context of detecting a light, and it is a common experience to find that a dim star will disappear when one 'looks at' it, but that it reappears when one looks to the side of it. Its disappearance under these circumstances can be explained by the fact that its luminance is below cone threshold, and its reappearance by the fact that its luminance is above rod threshold.

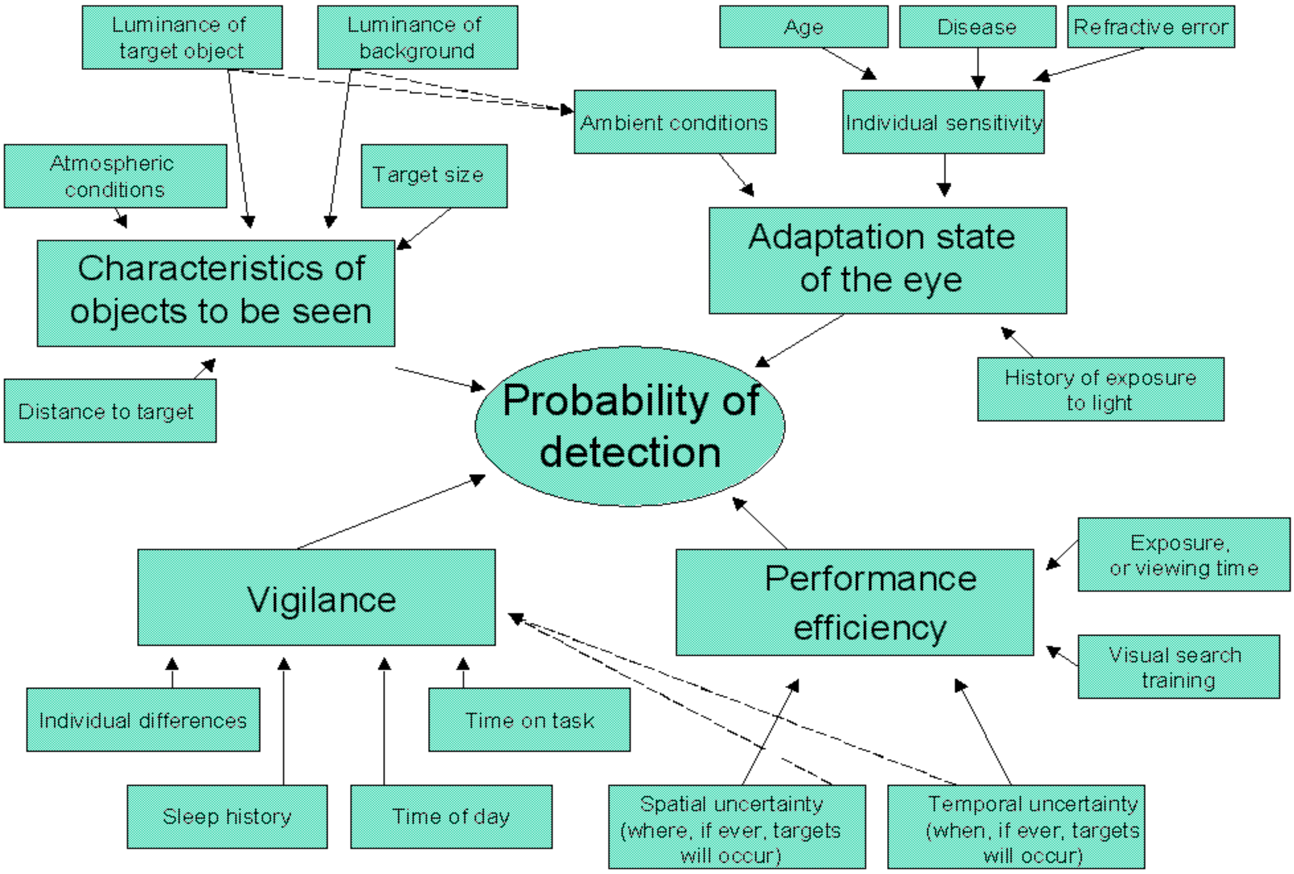


Figure 17 Factors affecting the probability of detection

Rods are present outside the fovea, and their density gradually increases with eccentricity (see Figure 1) reaching a maximum concentration at a point some 17 degrees from the fovea (13). Since the rods have a lower threshold than the cones, they are much more sensitive to light. A person attempting to see in scotopic illumination (light dimmer than moonlight) has to depend entirely on rods. To best detect small targets with the rods under such circumstances, the individual must look approximately 15-20 degrees to one side, above, or below an object to place the target object on the part of the retina that possesses the highest density of rods (120). In the case of bridge personnel onboard a ship, foveal vision is used for the examination of instruments and charts, but one would expect that peripheral vision, using rods, would be fundamental when scanning the visual environment (119;120).

7.1.1 Qualitative observations

From observations made during the ship visits, there appears to be a lack of structure or process to the lookout task. In practice the task involved looking out of the window and scanning the horizon, a consensus shared with the literature regarding visual search. Furthermore, based on feedback from crewmembers, there appears to be no formal training for Lookouts in terms of suitable search strategies. In this regard, Lookouts appear to be reliant on the experience gained through time served at sea. It is common experience that seeing in the dark is best accomplished by not looking directly at the object to be seen (120). Where any doubt exists about whether night time Lookouts are using an optimal strategy, then further training should be provided. Night lookout personnel can be taught to fixate to one side of an object to avoid the central blind spot (see section 7.1) and to scan, utilising the most sensitive part of the retina to improve target detection at night.

During the ship visits it was noted that Lookouts were using binoculars to confirm that they had identified an object of interest during their visual search. There are three factors relevant when considering the use of binoculars:

1. They could let more light into the Lookout’s eyes;
2. They could shield the eyes from the ambient light on the bridge;
3. They could be used to focus the image, hence correcting any refractive error (or night myopia) the Lookout may have.

In theory, for the image as a whole there is a trade-off between having a larger entrance pupil for the complete optical system (eye + binocular), and having a magnified image spread out over the retina. However, if we consider the yacht lamp as a point source, then the binoculars would have made it brighter as well as ensuring that the image was in focus.

7.2 VISION STANDARDS

It is essential that all seafarers meet the basic visual acuity and colour vision standards required to complete the duties associated with the navigational watch. International conventions (156) require that all seafarers over the age of 18 be examined for medical fitness every two years. These standards are based on high contrast photopic visual acuity, of which Snellen acuity is the standard optometric measure. Lines of letters are displayed as high contrast black figures on a white background. Visual acuity is measured by recording the size of the items in the smallest line on which most of the items can be identified (157). Normal Snellen acuity means being able to identify items that have an angular dimension of 1 min (1/60th of a degree) of visual angle.

The expression more commonly used for an individual’s visual acuity is the ratio of the distance at which the individual can read a line on a standard optician’s chart to the distance at which a person of normal sight can read that line (e.g. 6/12 means that the individual can just read at 6m the line which a normally sighted person can just read at 12m). However, a substantial limitation with this test is that it quantifies the person’s ability to *resolve* the detail of small, high contrast objects under well-lit conditions and does not necessarily predict an individual's ability to perform the actual task required of the Lookout, which is to *detect* a low contrast target in poor, demanding visual conditions (158). There is evidence to suggest that measures of a person's sensitivity to contrast are more useful than measures of acuity for predicting visual performance in real world tasks (159-163).

Under scotopic conditions, the luminance contrast sensitivity of a target quantifies its visibility relative to its immediate background (6). Objects can be seen at night only if they are either lighter or darker than their background and can be discriminated by subtle differences in contrast (145). In the absence of research specifically related to the maritime environment, it is possible to consider comparable evidence collected during the examination of night time driving. This evidence suggests that the reduction in contrast sensitivity experienced under low light conditions might be more important than changes in resolution.

For example, Wood and Owens (164) show that visual acuity measured under standard photopic testing conditions did not predict driver's target recognition while driving at night. After a dark adaptation period of 30 minutes, visual acuity and contrast sensitivity (Pelli-Robson chart) were measured while the participants wore goggles fitted with neutral density (ND) filters. Measures were made under four different luminance conditions: using 3.0 ND (6.5 cd/m^2), 2.0 ND (0.65 cd/m^2), and 1.0 ND (0.065 cd/m^2) filters and finally no filter (65 cd/m^2). Visual performance was assessed while participants drove under day and night conditions around a closed circuit track. There were 21 standard road signs located at random intervals around the track and participants were required to report all road signs. In addition to road signs, there were also low contrast road hazards (grey foam rubber blocks) placed at four locations along the circuit and at points along the track, and pedestrians wearing reflective markings walked along the hard shoulder of the opposite lane in the direction facing the driver. Visual performance was calculated as the percentage of signs, road hazards and pedestrians missed/identified correctly. Results show that target recognition ability under night time driving conditions was reduced compared to daytime conditions and that photopic contrast sensitivity, rather than visual acuity, provided the best prediction of target detection, especially under the dimmest night time condition (0.065 cd/m^2).

This suggests that sensitivity to contrast may be more useful for predicting recognition performance at night, a position supported by Glovinsky et al (165). In a study that compared more than 20 night vision tests, only three were found that could predict participants' ability to detect military targets at night: dark adaptation rate (DAR), scotopic retinal threshold (SRT) and mesopic contrast sensitivity (CS). Follow-up research to evaluate the reliability of these tests over a six-week period (166) found acceptable measurement stability for SRT and CS measures, but not the DAR. The reliability of the SRT was high, values at week 0 showed a high correlation with scores throughout the rest of the study. Initial measures of mesopic CS were found to be moderately correlated with scores obtained during follow-up measurement. However, DAR demonstrated low reliability, with no correlation between initial values and those recorded at subsequent assessments (the authors suggest that this may be a result of timing inaccuracies in the procedure applied).

Overall, SRT appears to be the most appropriate parameter for evaluation and prediction of night vision capability in the field during moonless nights, while mesopic CS is a more reliable parameter when the moon is half full. The investigators concluded that the assessment of the night vision of pilots and military personnel could be based on scotopic sensitivity after 30 minutes of dark adaptation and contrast sensitivity under mesopic illumination.

7.3 RETINAL ADAPTATION UNDER MESOPIC CONDITIONS

It is clear that the Lookout’s task is not well modelled by considering the dark adaptation function usually obtained in the laboratory or clinic, and to do so can easily give rise to incorrect interpretations because it is taken out of context. The starting point of the Lookout’s adaptation was lower than that used in the laboratory (a large bleach) and the end point was higher (total darkness). It is clear from the visits to the ships that the data in the literature does not allow us to model mathematically the Lookout’s task with any precision. Consequently, recommendations about the time the Lookout should adapt before starting their duties are based on an approximation of broadly comparable data. For example, Plainis et al (167), during an examination of night time driving performance, examined the time course of dark adaptation to mesopic levels of illumination.

Figure 18 shows retinal adaptation at a range of ambient illuminance levels after exposure to a 3200 cd/m^2 light source for one minute (again this is still much brighter than levels observed onboard the ships visited), in comparison to total darkness. It is clear that the retinal adaptation curve alters markedly with ambient lighting. In total darkness there is a clear rod-cone break, which occurs at around the 7minute mark and the rods require around 15 minutes to reach the absolute threshold of around 10^{-5} cd/m^2. However, at upper mesopic levels (5.0 lux) only a single curve is observed, which undergoes a monotonic increase in sensitivity that can be attributed to cone mediated vision only. Similarly, at 0.5 lux no break is evident, suggesting that the rod recovery is desensitised by the cone system, which dominates at these levels. If ambient illuminance is decreased to 0.1 lux (low mesopic levels), the rod-cone break is present and a second, rod-dominated phase of adaptation can be distinguished, representing the switch between cone and rod-mediated vision.

At the light levels observed on the ship visits (0.1 lux) the rod-cone break is delayed compared with that for absolute darkness. Under these conditions, the rods would be sensitive enough to detect the test light at around 8 minutes after which, significant improvements in threshold sensitivity occur. However, threshold sensitivity under mesopic light levels (after 15 minutes) is reduced by around 2 log units in comparison to complete darkness. As a consequence, the Lookout would never be fully dark adapted, and would therefore need less time after entering the bridge to reach a steady state of adaptation.

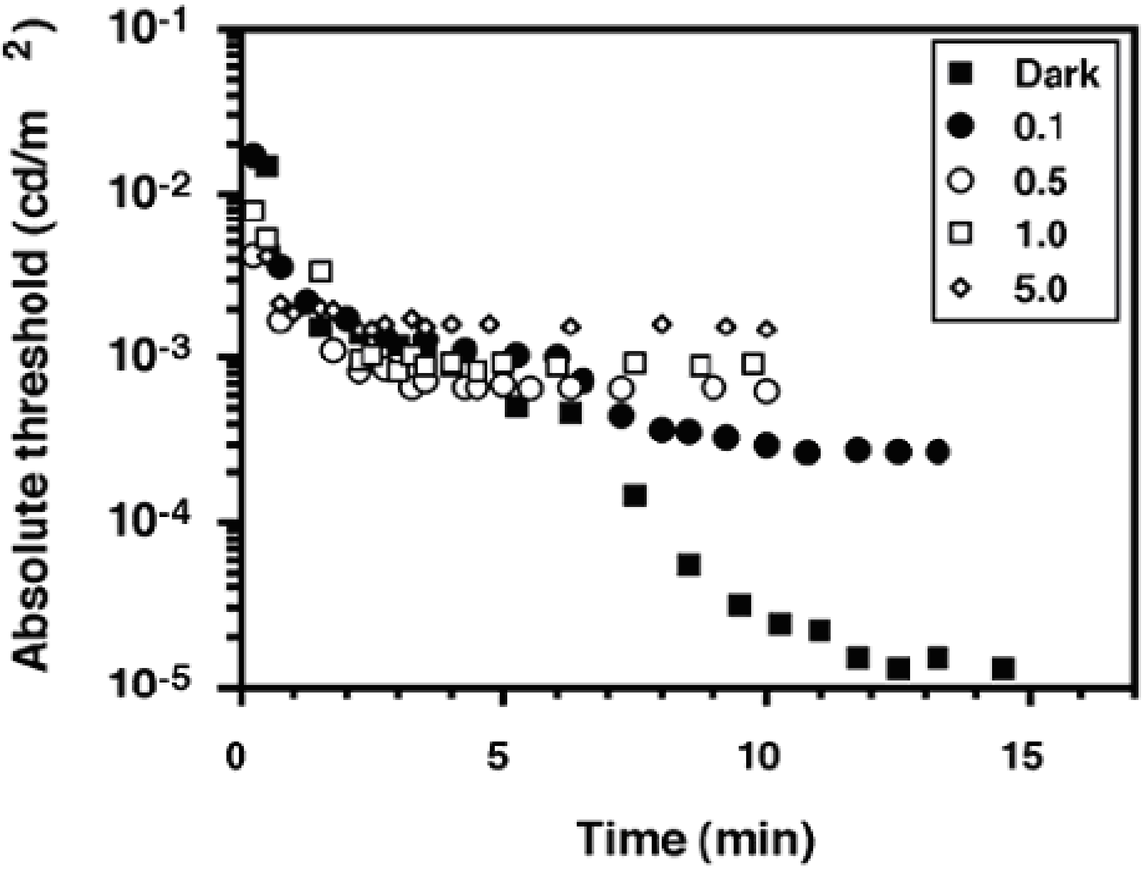


Figure 18 Retinal adaptation curves compared with the classical dark adaptation curve (filled squares) for four mesopic levels (5.0 – triangles, 0.5 – circles and 0.1 lux – filled circles) of background luminance (adapted from 167)

7.4 CHARACTERISTICS OF OBJECTS TO BE SEEN

Several factors influence the probability that a Lookout will detect a target object at sea including, the luminance of the background, the luminance of the target, atmospheric conditions, target size, distance to target, etc. As previously stated, it is not possible to accurately measure these elements in the field. However, the lookout task is predominantly reliant on positive contrast, as the Lookout must identify the relatively bright navigational lights of other ships against the dark background of the night sky or the sea and it is possible to specify target objects in terms of Annex 1 (Positioning and technical details of lights and shapes) of the International Regulations for Preventing Collisions at Sea, 1972, as amended (COLREGS). The technical requirements for navigation lights provide the distribution of luminous intensity and colour of lights for the masthead light, sidelights, stern lights, etc. Rule 22 (visibility of lights) states that the navigational lights must be visible at the following minimum ranges:

(a) In vessels of 50 metres or more in length:

- A masthead light, 6 miles;
- A sidelight, 3 miles;
- A towing light, 3 miles;
- A white red, green or yellow all-round light, 3 miles.

(b) In vessels of 12 metres or more in length but less than 50 metres in length:

- A masthead light, 5 miles; except that where the length of the vessel is less than 20 meters, 3 miles;
- A sidelight, 2 miles;
- A stern light, 2 miles;
- A towing light, 2 miles;
- A white, red, green or yellow all-round light, 2 miles.

(c) In vessels of less than 12 metres in length:

- A masthead light, 2 miles;
- A sidelight, 1 miles; a towing light, 2 miles;
- A white red, green or yellow all-around light, 2 miles.

7.4.1 Luminous range of navigational lights

Given the observation that illuminance levels onboard the bridge fall in the mesopic range, it is important to determine the necessary luminous range of a navigational light, in order for it to be seen within the conditions set out in COLREGS. The luminous range of a light is defined as the maximum distance at which a light can be seen, as determined by the luminous intensity of the light, the meteorological visibility, and the threshold of illuminance at the eye of an observer (i.e. the ambient light level on the bridge). The further the observer is from a light the more its beam has spread out so less light will enter the eye. In addition, any haze in the air will attenuate the beam. This can be expressed in mathematical terms using Allard's Law (168).

$$E = \frac{I * T^{D}}{D^{2}}$$

where:

E = Illuminance at the eye of the observer (lx)
I = Luminous intensity of the light (candelas)
T= The transmissivity of the atmosphere, defined as the ratio of the amount of light that exits a unit length of atmosphere to the amount of light that entered the unit length of atmosphere
D = The distance between the observer and the light (metres)

Allard’s Law may be rearranged to solve the required intensity of a light signal to produce a given value of illuminance at some distance under specific conditions of visibility, thus:

$$I = \frac{E * D^2}{(0.05)^{\frac{D}{V}}}$$

The resultant nominal range should be calculated in metres, converted to nautical miles and rounded off to the nearest nautical mile.

Allard's Law allows the calculation of the illuminance (E) as a function of distance (d), luminous intensity (I) and meteorological visibility (v). Meteorological visibility is the greatest distance at which a black object of suitable dimensions can be seen and recognised by day against the horizon sky or in the case of night observations, could be seen and recognised if the general illumination were raised to daylight level.

$$E(d) = \frac{I \times 0.05^{\frac{d}{v}}}{3.43 \times 10^6 \times d^2}$$

In the case of a light that appears as a point source, the luminous range D is defined as the maximum distance at which a light can be seen, as determined by the luminous intensity I of the light, the meteorological visibility V and the illuminance E at the eye of the observer. At this maximum distance, the illuminance E at the observer's eye is reduced to the value E_t. It is possible therefore to derive the intensity (I) required for a given luminous range (D) at a given visibility (V).

$$I = (3.43 \times 10^6) E_t D^2 (0.05)^{-\frac{D}{V}}$$

A selection of figures derived from the formula is given in Table 9. The figures highlighted in the third column are the minimum levels of luminous intensity (cd) required to satisfy the requirements specified in Rule 22 (visibility of lights) of COLREGS, at the ambient light levels observed during the ship visits. These figures reflect the fact that threshold sensitivity, referred to as illuminance in Table 9, is around 2 log units lower under low mesopic conditions than under scotopic conditions (first column, Table 9).

Table 9 Nominal range calculation for night time luminance values

	Conditions		
Background lighting	None	Minor	Substantial
Illuminance (lx)	2.00E-07	2.00E-06	2.00E-05
Transmissivity (per NM)	0.80	0.80	0.80
Visibility (NM)	13	13	13
Range (NM)	Intensity (cd)		
1	0.9	9	90
2	4.3	43	430
3	12	120	1,200
4	27	270	2,700
5	52	520	5,200
6	94	940	9,400

7.4.2 Observation of navigation lights

When observing the navigation lights of one commercial vessel from another commercial vessel it is not unusual to be able to see the lights of the other vessel well in excess of the minimum ranges specified in the COLREGS. Reports from experienced mariners suggest that under favourable circumstances it is possible to see the lights of other commercial vessels at up to twice the specified minimum. Whether this is because the manufacturers of navigation lights fitted to commercial vessels exceed the minimum specifications set out in the COLREGS or due to the relative heights they are fitted and observed from in commercial vessels is not known.

As both ship visits were carried out during the winter months, and hence out of season for leisure craft activities, it was not possible to make any observations of leisure craft navigation lights. Therefore it was not possible to relate the minimum ranges specified in the COLREGS with actual minimum ranges when leisure craft navigation lights were observed. However experienced mariners have also indicated that the problem of observing navigation lights of other vessels from the relatively lofty height of a commercial vessel's bridge becomes greater as the other vessels become smaller, with the navigation lights of leisure craft being notoriously difficult to see.

A small sailing vessel is only required to exhibit sidelights and a stern light, and these may be as little as one meter above the waterline. The specification of navigation lights contained in the COLREGS has evolved over centuries from the days of sailing ships when vessels observed each other from similar heights and travelled at much lower speeds. The present regulations make some attempt to overcome the disparity between the sizes of vessels (and allow for heeling and rolling motion) by specifying a vertical arc through which navigation lights must be visible; however even then the lights of sailing vessels are only required to have 50% intensity at the limits of the vertical arc. This makes the detection of sailing vessels navigation lights particularly difficult as they are always heeled over by the effects of the wind, which is fine when observing the sailing vessel from upwind (the navigation lights are angled upwards), but not so when observing from downwind (the navigation lights are angled downwards).

Another factor relates to the limited electrical power on leisure craft, and particularly sailing leisure craft. As a result, navigation lights designed for leisure craft may just meet the minimum specifications in the COLREGS. This is particularly pertinent when it is further considered that owing to background lighting levels on a commercial vessel's bridge the lookout will be operating almost exclusively in the mesopic range of dark adaptation and in order for navigation lights of other vessels to be seen at minimum specified range their intensity needs to be increased by 2 log units (see 6.3, Table 8). These factors, together with the effects of heeling, mean that the lights of a small sailing vessel are unlikely to be reliably visible at the specified minimum range under modern bridge lighting conditions even by an observer who is fully dark adapted to these lighting conditions.

It is therefore reasonable to conclude that the configuration and specification of navigation lights relating to small craft needs to be reassessed with a view to improving their minimum detection range in realistic operating conditions. Alternatively, consideration could be given to moving the lookout position from the bridge to a location where the level of dark adaptation is in the scotopic vision regime and the vertical level as low in the ship as is practical. In practice this would entail a return to posting a lookout on the forecastle or forward main deck section of vessels without a forecastle, which in itself presents its own problems. The fore part of commercial vessels is an exposed position and some protection from the elements would need to be provided so that the lookout is operating in a safe comfortable environment to enable concentration on the task of lookout. Also, a means of safe access to and egress from the lookout position will need to be provided. However, there will be occasions when adverse weather and sea conditions make this lookout position untenable.

In certain types of vessel such as Cruise and RoPax vessels it may not be possible to find a suitable location that is in the scotopic vision regime due to the proximity of deck lighting. There will also be manning issues to consider if the OOW is not to be left as the only person on the bridge at night as a consequence of moving the lookout to another location. Even if the separate lookout position is only required to be used in near coastal waters, to be effective a substantial number of the world's merchant fleet would be affected and this would require international agreement within IMO to alter the appropriate international conventions. Also, the question needs to be asked whether or not it is reasonable to expect the majority of World commercial shipping to incur the responsibility to protect a small minority of leisure vessels when relatively minor modifications to leisure vessel navigation lights would serve the same purpose?

7.5 OTHER PERFORMANCE INFLUENCING FACTORS

One of the aims of this analysis was to determine the demands associated with maintaining a safe navigational watch and to identify what other factors are present that could influence the performance of night time lookout duties.

7.5.1 Perceptual impacts on night vision performance

The effects of decreased illumination on operational visual function can be dramatic (146). There are several factors that affect night vision performance that may be important depending on the task-specific factors associated with lookout duty.

- **Central Blind spot at night:** As discussed in Section 7.1, when in conditions with low light levels, individuals may not be able to see an object when they look at it directly (i.e. when they fixate on it), but can see it when they look to one side of the object.

- **The Mandlebaum effect:** Mandlebaum (169) reported an informal experiment in which he asked participants (family and friends) to read a sign from varying distances within a screen-enclosed porch. It was found that for each participant there was a critical distance from the screen (around one meter; 170) at which they could no longer read the sign, despite being able to read it from both further away and closer to the screen. When questioned, participants reported that they could not avoid focusing on the screen when viewing the sign from the critical distance. This reflects a tendency for the accommodation mechanism to preferentially focus on the stimulus nearest the dark (resting) focus position (171;172). This phenomenon may affect the performance of the Lookout if the windows are not kept clean, if rain and sea spray are allowed to build up on the windows or during foggy conditions and the Lookout(s) stand around 1m from the window.

- **Night myopia:** This is a specific tendency of accommodation to regress to its resting position under reduced illumination or degraded stimulus conditions. As luminance decreases, the ability to adjust focus diminishes until accommodation reaches a fixed position know as the ‘dark focus’ which is the distance of accommodation in complete darkness. The dark focus of the eye may become a problem whenever there is a lack of adequate visual stimulus upon which to focus. For most people, night myopia has a relatively minor effect because no visually resolvable distant target is present when it occurs. When a target does become visible, the eye rapidly readjusts (173-176).

7.5.2 Length of watch

Given the nature of the lookout task, the duration of the watch is a particularly relevant factor in terms of performance. The bridge team typically spend several hours on watchkeeping duty before being relieved (177), normally two watches of 4 hours, separated by an 8 hour rest period as was the case on the tanker visit. However, the RoPax vessel Lookouts operated on a ‘6 hours on, 6 hours off’ watch rotation (a typical watch pattern on short sea trade vessels). Since this is an activity that makes considerable attentional demands, long periods of work may give rise to vigilance decrements, which are frequently reported in such situations (178;179). There is a negative impact on vigilance during prolonged exposure to a task, which can be exacerbated if the task is particularly monotonous (180). Typically, the ability to detect critical signals drops rapidly from the onset of a vigil and then stabilises at a significantly lower level within 25 to 35 minutes (181). This decline in performance is consistent across varying contexts and has been labelled the vigilance decrement (182).

7.5.2.1 Vigilance

The lookout task is a detection task reliant on the ability of the bridge team to identify relevant targets (e.g. other vessels) and to discern between signal and noise. They are then required to interpret what they have seen in terms of the subsequent actions e.g. collision avoidance manoeuvres. The lookout task requires the operator to constantly monitor the environment over the duration of their watch. The ability to focus one's attention and to maintain perceptual sensitivity to change in stimuli for a relatively long period of time is referred to as vigilance (182;183). Vigilance deficits and their direct consequences on safety are increasingly considered a major problem, especially in the field of transport (184). Lapses in alertness during watchkeeping may have severe consequences (i.e. collision).

Vigilance is linked to the psychological construct ‘sustained attention’, which describes a fundamental component of attention characterised by a readiness to detect rarely and unpredictably occurring signals over prolonged periods of time (179;185). Given the major role that vigilance plays in contexts requiring sustained attention, maintaining alertness to information provided visually is an important aspect of the lookout task and is an obvious topic for any discussion of maintaining a lookout. Research generally indicates that when engaged in such attention-intensive and monotonous tasks, retaining a constant level of alertness is extremely difficult, particularly when confronted with a task that demands a high levels of vigilance for the appearance of weak or transitory signals (186).

The classic example of the vigilance decrement is the Mackworth clock test (187). Designed with the intention of improving the performance of radar operators, participants were required to observe a clock-like device, complete with a pointer that moves to a new position every second, looking for double step movements (the target) among single step movements (the non-target). Target events were set to occur at irregular intervals at a rate of 12 events each 30 minutes. Participants were required to respond to targets with a key press. Results indicate a decline in detection rate with time on task, in that there was a 25-30% loss of target detection efficiency within the first 60 minutes of the vigil with at least half that amount occurring in the first 15 minutes of task performance. Beyond the 60-minute mark, performance degrades more slowly before a plateau effect is observed. The clock test methodology has been applied using a variety of interval schedules and the results have been found to be remarkably robust. Subsequent studies have shown that vigilance could be improved by having shorter working periods, taking breaks and being given feedback (188;189).

Performance efficiency in vigilance tasks is closely linked to the nature of the stimuli that demand attention. Several factors have been identified that will influence efficient performance of vigilance tasks including sensory modality of signals, the salience of signals, the characteristics of the background (non-target events) in which the critical (target) signals are embedded and task complexity (182;190-193). In particular, the Lookout is faced with considerable uncertainty regarding the target signals they are to detect. They may not know when such signals will appear (temporal uncertainty) or where they will appear (spatial uncertainty) and both have been shown to degrade performance. When critical signals are presented more frequently (lowering the temporal uncertainty) the speed and accuracy of signal detection is improved (194;195). Furthermore, under such conditions performance efficiency is lowered and subjects tend to bias their attention towards those portions of the display in which the likelihood of signal appearance is highest (195;196). This is demonstrated in the link analysis of the RoPax bridge (Figure 3), which shows a bias towards the portside of the bridge, reflecting the position of the ship relevant to the flow of traffic encountered en route.

With regard to the issue of stimulus uncertainty, several studies have revealed an important effect of training. Griffin et al (197) assessed the affect of expectancies generated during pre-test training on the performance efficiency in subsequent trials. Those who were exposed to a high signal probability during the pre-test detected more signals in the main watch than those exposed to a low pre-test probability, regardless of the signal probability in the vigil itself (high or low). The vigilance decrement was steeper under conditions of low as compared to high-test probability. This finding is strongly suggestive of the potential of training to help minimise the influence of signal uncertainty in practical contexts. However, based on both feedback from crewmembers and an examination of STCW 78, MGN97 and MIN303 there appears to be no formal training for lookouts in terms of suitable search strategies. In this regard, lookouts appear to be reliant on the experience gained through ‘time served at sea’.

An additional component that will affect the performance of the lookout is time of day. Several biological processes follow a circadian rhythm such as the sleep wake cycle, body temperature and cardiovascular function, among others. Studies have shown that even after a normal night’s sleep vigilance tends to decrease periodically and at least twice during the 24hrs, between 13:00 and 16:00 and particularly between 01:00 and 06:00 (198;199). This suggests that lookouts are trying to maintain performance efficiency during the worst time of day for doing so. This would be particularly relevant on the RoPax vessels with a six-hour watch rotation, where, in order to successfully detect hazards, more frequent staffing changes may be needed to successfully detect hazards.

7.5.3 Mental underload

Excessively low workload can affect the performance of the navigational watch. Automated systems in particular have the potential for imposing underload by significantly reducing task demands. Supervisory control during the navigational watch involves large periods of time where nothing noteworthy happens and both the OOW and the Lookout are only required to perform routine tasks. They are required to intervene when the system fails and then for only brief periods during the watch. If the maximum capacity of an operator has been limited as a consequence of the task, they may not be able to cope with any subsidiary tasks, or when an emergency situation arises e.g. if the automation fails, and they are suddenly faced with an increase in task demand (195). The Lookout may be particularly affected by underload.

Attentional resource theories make a common assumption about performance; if demand exceeds the capacity of a fixed cognitive resource, performance will degrade (179;200;201). Within this framework, low levels of task demand should not exceed attentional capacity and, therefore should not lead to a decrease in performance. In fact at low levels of task demand, all attentional resources should be available for the task, leading to optimum performance. However, this does not adequately explain performance decrements observed using low demand tasks. For example, Desmond and Hoyes (202) found unexpectedly high errors in low workload conditions on an air traffic control task. This has been used as evidence to support the notion that operators use less efficient resource allocation strategies under conditions of underload and as a consequence are failing to match their effort appropriately to the task. Malleable Attentional Resources Theory (MART; 203) suggests that the size of the relevant resource pool varies in line with cognitive workload, such that excessive reductions in cognitive workload shrink available capacity thus explaining the apparent performance decrement observed in low demand tasks. This may also explain why previous research has shown that vigilance tasks place high mental workload on the operator (204); if operators consider the workload of a task to be excessive they may behave as though they are overloaded, even though the task demands are objectively low (205;206).

7.5.4 Automation

Modern ship bridges are highly automated man-machine systems where the Integrated bridge system combines the wide number of automated systems (e.g. radar, ARPA, ECDIS etc) to produce a suite of controls that make it possible for a single person to act as the Helmsman, Lookout and OOW (207). Safe and efficient performance is heavily dependent upon how functions are allocated between the human and the machine and the ability of watchkeepers to perceive, interpret and make decisions upon information acquired from the surrounding environment (208). However, the introduction of increasingly complex automated control systems has fundamentally changed the role of the watchkeeper (148). During the watch, the OOW can be considered the active manager of a system (i.e. the ship) that includes both automated systems e.g. ARPA, ECDIS, and a human element (i.e. the Lookout). In this supervisory control role the navigator specifies the goals, constraints and procedures in terms of the automated systems rather than controlling the process directly (148).

The shift to supervisory control has led to three general performance problems. First, humans have to carry out more monitoring activities, a task at which they are not particularly good (209), as demonstrated by the research on vigilance (204). Second, increasing the level of automation has also tended to extend the human operator’s span of control, as it becomes possible for more systems to be managed by the individual. Watchkeepers are increasingly responsible for secondary task functions such as engine and cargo control, in addition to the primary task of navigation. This requires cognitive resources to be deployed across several tasks, in order to maintain overall performance (210). Finally, the main role of the human supervisor is to intercede when there is a system failure (211). Under these circumstances, levels of workload may become excessive, for example during collision encounters or high traffic density manoeuvres in confined waters, as users are required to use their specialist knowledge to compensate for the failure of the automated system. However, the infrequent and changing nature of each emergency means that there is little chance to gain such knowledge and experience in terms of practiced procedural responses. Furthermore, such skills deteriorate when they are not used and a formerly experienced operator who has been monitoring an automated system may become an inexperienced one (179).

8 CONCLUSIONS

Data collected from the observation of night time duties on the bridge and information from informal interviews, conducted with members of the bridge crew, were used to identify the activities associated with maintaining a safe navigational watch. Results of the task analysis indicate that much of the task of maintaining a safe navigational watch is characterised by activities involving basic control of the vessel, such as maintaining appropriate speed, course and position. However, the key component of determining a safe course is maintaining a safe navigational watch, the aim of which is to avoid collision by identifying ships, navigation marks, and floating debris identified as potential dangers to navigation that may cross the ship’s path. With respect to the aims and objectives of this study the following conclusions can be drawn:

With respect to dark adaptation:

- On moving from an environment with higher ambient light levels to one with lower levels, the sensitivity of the eye changes (increases), and the time taken to reach the new steady-state of sensitivity will depend upon the difference in light level.

- The processes of dark adaptation, and its effects on visual performance have been investigated in detail previously under laboratory conditions, but there are no studies relating specifically to modern merchant ship bridge conditions, and no experimental data that can be easily applied in the current context.

- Under laboratory conditions, very bright pre-adapting lights are used, and it can take up to 40 minutes for the eye to adapt to complete darkness. However, it is highly unlikely that the bridge crew will, prior to commencing night time lookout duties, be exposed to comparably bright pre-adapting lights.

- Lighting levels on the bridge are such that only partial dark adaptation occurs. As a consequence, the Lookout’s eyes would never become fully dark adapted, and it would therefore take less time after entering the bridge for the eyes to reach their steady state of adaptation.

- Adaptation to lighting conditions on the bridge will normally be achieved in 15 minutes, but there are a range of personal factors that influence this.

With respect to individual characteristics:

- There are a range of individual differences that influence the rate of adaptation and the threshold sensitivity achieved. For example, dark adaptation has been shown to slow with increasing age.

- The tests currently used to routinely assess seafarer's vision are poor predictors of performance under night time conditions on a ship's bridge.

With respect to the bridge environment:

- The watch handover periods observed were shorter than the timescales recommended in both IMO MSC.1/Circ.1280 and the bridge procedures guide.

- Light levels on the bridge were well within the recommended standards.

- Light levels in the chartroom of the ships visited were higher than the recommended maximum levels.

- The navigational watch involves large periods of time where nothing noteworthy happens, and both the Officer of the Watch and the Lookout are only required to perform routine tasks. This can create excessively low workload (underload) that affects performance.

- Vigilance may be as important as dark adaptation in the detection of dim lights at night. There is a negative impact on vigilance during prolonged exposure to a task, which can be exacerbated if the task is particularly monotonous.

- Night time Lookouts are trying to maintain performance efficiency during the worst time of day for doing so. Vigilance tends to decrease periodically at least twice during 24 hours, typically between 13:00 and 16:00 and 01:00 and 06:00.

With respect to the external environment:

- The intensity and position of navigation lights on larger vessels is such that the sensitivity of the eye under normal ambient bridge illumination conditions is likely to be sufficient for their visibility to be acceptable. This may not be the case for poorly lit small craft.

9 POINTS FOR FURTHER CONSIDERATION

The following points for further consideration are raised as they may protect, improve or maintain the operational night vision of seafarers.

9.1 WITH RESPECT TO DARK ADAPTATION:

Conduct further research to produce appropriate adaptation data using a simulated ship's bridge as current laboratory and clinical data, is not easily applied to modern merchant ship bridge conditions.

It is clear that the Lookout's task is not well modelled by considering the dark adaptation function usually obtained in the laboratory or clinic, and to do so can easily give rise to incorrect interpretations because it is taken out of context. The starting point of the Lookout's adaptation was lower than that used in the laboratory (a large bleach) and the end point was higher than that used in the laboratory (total darkness). It is clear from the visits to the ships that the data in the literature does not allow us to model mathematically the Lookout's task with any precision. Consequently, recommendations about the time the Lookout should adapt before starting their duties are based on an approximation of broadly comparable data e.g. Plainis et al (167). To accurately define the amount of time required to dark adapt under the conditions observed onboard, it is necessary to conduct further research with the purpose of:

- Evaluating the time required to reach a steady state adaptation level at the light levels observed on the ship visits;
- Determining whether this time, and the sensitivity level achieved, varies with age and refractive error;
- Examining the benefits of Electronic Chart Display and Information Systems (ECDIS) in relation to the management of dark adaptation; and
- Examining the use of red light/ red filtered goggles to maintain dark adaptation of the rod photoreceptors of the eye.

Examine the benefits of Electronic Chart Display and Information Systems (ECDIS) in relation to the management of dark adaptation

The need to leave the wheelhouse and enter the chartroom was identified as a significant factor affecting dark adaptation. The tasks associated with entering the chartroom are plotting the ship's position and monitoring the track, checking and updating the passage plan, and maintaining the deck log. The bridge teams on the RoPax vessels made far fewer and shorter visits to the chartroom in comparison to the bridge teams on the tanker. One possible explanation for the differences observed is that the RoPax vessels were fitted with ECDIS as part of the integrated bridge system. The revisions of Chapter V (Safety of Navigation) of SOLAS (2002) allow ECDIS to be accepted as meeting the chart carriage requirements; by 1st July 2018 the carriage of ECDIS will be mandatory on the majority of new and existing vessels. However there will still be a significant minority of vessels that will not be required to carry ECDIS. For example:

- Passenger ships of less than 500 gt;
- Tankers of less than 3,000 gt;
- Cargo ships of less than 3,000 gt;
- Existing cargo ships constructed before 1st July 2013 of less than 10,000 gt.

The use of ECDIS reduces the need to use paper charts and therefore should reduce the need for the bridge team to visit the chartroom. Further research would be needed to quantify the impact of ECDIS on the frequency and length of visits to the chartroom. Also, further research would be needed to assess the impact of the significant minority of vessels that will not be required to carry ECDIS. In addition to the use of ECDIS there are other navigational techniques, such as radar parallel indexing plus clearing bearings and ranges, which can reduce the need to visit the chartroom and hence can be employed in the management of dark adaptation. Consideration could be given to promoting their use in this context, particularly on those classes of vessels not required to carry ECDIS.

Examine the use of red light/red filtered goggles to maintain dark adaptation

It is generally accepted that red light, or red tinted goggles, can preserve the dark adaptation of rods (125-129). Dark adaptation is considerably faster after exposure to red light than after white light adaptation (27). The rationale for the use of red light is based on the differences in spectral sensitivity between the rods and cones. Light with wavelengths greater than 610 nm does not affect rods, so the use of bright red light on the bridge will not affect adaptation. It does not, however, remove the need to adapt in the dark. Furthermore, red light should be avoided where colour discrimination is required, as red light will reduce the contrast of any red detail that may be present on navigational charts.

9.2 WITH RESPECT TO INDIVIDUAL CHARACTERISTICS:

Limit daytime exposure to sunlight

Exposure to excessive glare or sunlight during the day can produce a temporary but cumulative effect on dark adaptation. Studies have shown a significant decrease in performance of the rods after prolonged exposure to bright light (142;212;213). Around three hours of bright sunlight exposure has been shown to delay the onset of rod dark adaptation by 10 minutes or more and to increase the final threshold, so that full night vision sensitivity could not be reached for hours (144). After 10 consecutive days of sunlight exposure, the losses in night vision were reported to cause a 50% loss in visual acuity, visibility range and contrast discrimination in the dark (145). Repeated daily exposures to sunlight prolong the time to reach normal scotopic sensitivity, so that eventually normal rod sensitivity may not be reached (146). Wearing sunglasses during the day can reduce the impact of sunlight and protect the eyes for night duty. Similarly, those selected for lookout duty should avoid looking directly at any brightly illuminated objects.

9.3 WITH RESPECT TO THE BRIDGE ENVIRONMENT:

Reinforce current standards (15 minute recommendation) regarding dark adaptation

The current 15 minute recommendation for dark adaptation, defined in the Bridge Procedures Guide (147) and MSC.1/Circ.1280 (153), is sufficient, given that watchkeepers are not likely to be adapting from bright light levels. At the light levels observed on the ship visits (0.1 lux) the rod-cone break is delayed compared with that for absolute darkness. The rods would be sensitive enough to detect the test light after around 8 minutes, and significant improvements in threshold sensitivity should occur during the subsequent 10 minute period. However, it would be useful to reinforce this guidance, as the length of handovers observed during the ship visits were less than the recommended 15 minutes. Furthermore, on some large vessels, crew alternate periods on the bridge with periods of safety checks and fire watches in other parts of the vessel, some of which will be brightly lit. It should be noted that the same period of dark adaptation would be required every time the Lookout returns to the bridge. The illuminance levels on the bridge observed during the ship visits were within the recommended limits defined in guidance on ergonomic criteria for bridge design (214), which suggests a fundamental understanding of best practice associated with blackout procedures, i.e. radars and console lights were appropriately dimmed and the chartroom was curtained off, avoiding contamination from residual light.

Reinforce lighting standards contained in ergonomic criteria for bridge design

The need to enter the chartroom has been identified as a significant factor affecting the dark adaptation of the bridge crew. Although the ships visited were very good at following the blackout procedures and maintaining appropriate light levels on the bridge, it appears, based on illuminance measurements that less consideration is given to light levels in the chartroom. The illuminance readings in the chartroom were significantly higher than recommended in guidance on ergonomic criteria for bridge design (214) and would cause the eye to readapt to light, even if exposure to the light was brief. Light levels on the RoPax vessels were approximately 7 times the recommended maximum and approximately 3 times the recommended maximum in the tanker chartroom.

Limit the time spent performing lookout duty

The lookout task requires the crew member to constantly monitor the environment over the duration of their watch. Research generally indicates that when engaged in such attention-intensive and monotonous tasks, retaining a constant level of alertness is extremely difficult, particularly when the task demands high levels of vigilance for the appearance of weak or transitory signals. Since this is an activity that makes considerable attentional demands, long periods of work may give rise to vigilance decrements (178;179). Evidence has shown that vigilance could be improved by having shorter working periods (188;189). This would be particularly relevant on the RoPax vessels, where a '6 hours on, 6 hours off' watch rotation was implemented. In order to successfully detect hazards, more frequent staffing changes may be needed.

9.4 WITH RESPECT TO THE EXTERNAL ENVIRONMENT:

Examine the configuration and specification of navigation lights in respect of small craft

Given the difficulties of observing the navigation lights of small vessels together with the enormous practical difficulties of changing the practice of commercial vessels in moving the lookout to a more favourable position for the detection of these lights, as outlined in section 7.4.2, consideration should be given to increasing the minimum specified range of sidelights in vessels of less than 12 metres in length from 1 mile to 2 miles such that the minimum range of all lights on vessels in this size is 2 miles. One mile does not give much time to observe and take avoiding action if required, particularly on modern relatively fast vessels such as RoRo ferries and container vessels.

In addition sailing vessels of less than 12 metres in length, in recognition of the majority of time spent heeled over due to the effects of the wind and consequent effect on the visibility of their navigation lights when viewed from the downwind side, should have the option of displaying a single all round masthead white light instead of side lights and a stern light. The vertical arc of visibility of this masthead white light should be increased to 45 degrees above and below horizontal.

This all round white light can then also be displayed in conjunction with the sidelights when under power, as allowed under the current regulations, and as an anchor light. These modifications would have the practical benefits of not only increasing the potential detection range of these vessels but also allow an economy in the number of lights to be fitted and overall power consumption. The implementation of these changes would require the COLREGS to be modified necessitating international agreement at the IMO. In the meantime consideration could be given to adopting these changes for leisure craft that operate exclusively in UK territorial waters.

9.5 WITH RESPECT TO CURRENT REGULATIONS AND GUIDANCE:

Examine the scope for adding measures of sensitivity to contrast under mesopic and scotopic conditions to the seafarers' eye test

International conventions require that all seafarers over the age of 18 be examined for medical fitness every two years. It is essential that all seafarers meet the basic visual acuity and colour vision standards required to complete the duties associated with the navigational watch. These standards are based on photopic visual acuity and in their current form are an inadequate measure of the abilities required to perform lookout duties. It is necessary to conduct further work to develop a procedure for the evaluation of a Lookout's ability to detect a light that is equivalent to the dimmest yacht lamp and to incorporate this into the Lookout's certification requirements. In addition, it may be beneficial to develop a procedure for the evaluation of a Lookout's ability to detect such lights prior to taking part in the watch period. Similarly, evidence has been presented to suggest that scotopic retinal threshold (SRT) and mesopic contrast sensitivity (MCS) are better predictors of the ability to detect targets at night (164;215-217). Overall, SRT appears to be the most appropriate parameter for evaluation and prediction of night vision capability in the field during moonless nights, while MCS is a more reliable parameter when the moon is half full. Adding these tests to the standard acuity test may supplement the current vision standards. However, given that current certificates last for up to 2 years (depending on the seafarer's age), it would be necessary to examine the reliability of these measures over a similar time course before incorporating them into the existing medical standards.

Examine the scope for selecting Lookouts on the basis of mesopic and scotopic vision testing

The dark adaptation process includes individual differences in the rate of dark adaptation and the final threshold of night vision capacity (9). A benefit of including measures of SRT and MCS as part of the vision standards is that it would be possible to identify those seafarers with the best mesopic and scotopic vision (9). Similarly, it would identify those seafarers not suited to night time lookout duty. For example, there is a considerable body of evidence that demonstrates the association between age and a slowing of the process of dark adaptation. A number of classic studies have revealed age-related reductions in minimum threshold sensitivity ranging from 0.3 to 2.0 log units in magnitude (63;64;66;218-220). It is therefore reasonable to conclude that some older seafarers will have greater difficulty in satisfactorily performing the duties associated with the lookout task at night. However age alone would not determine the suitability of seafarers to undertake night time lookout duty.

Examine the scope for the introduction of visual search training

Dark adaptation alone is not sufficient to ensure the highest level of Lookout performance. Based on both feedback from crew members and an examination of STCW 78, MGN 97 and MIN 303, there appears to be no formal training for Lookouts in terms of suitable search strategies. In this regard, Lookouts appear to be reliant on the experience gained through time served at sea. It is common experience that seeing in the dark is best accomplished by not looking directly at the object to be seen (120). Night lookout personnel must be instructed in the practical applications of this phenomenon. Individuals can be taught to fixate to one side of an object to avoid the central blind spot (see section 7.1) and to scan, utilising the most sensitive part of the retina to improve target detection at night. The US Naval Education and Training Command (221) provides some basic principles for successful visual search at night:

- Keep your eyes moving. Quick short movements and short pauses are better than long sweeping movements and long pauses. The eyes do not see well when they are moving; don't sweep the sky or the horizon with the eyes.

- Scan the horizon in a series of movements, which will allow your eyes to come to a periodic rests as they scan the sector.

- When viewing objects at night, always look a little to one side and out of the corner of your eyes. Pay attention to the things on the outer edges of your field of vision. A faint object may not be recognisable until your gaze has been directed towards it a number of times.

- Likewise, direct your eyes slightly above or below the horizon, as there are times when you cannot see the actual horizon unless you line of sight is purposely elevated or depressed.

- One of the greatest aids to night vision is the contrast between object and background. Therefore, a good technique is to concentrate on the point where the sky appears to meet the water. Here objects may loom above the darker water and be seen against the lighter sky.

- Practice what you know about seeing at night until it becomes second nature for you to use your eyes to their best advantage.

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11 GLOSSARY

AIS	Automatic Identification System
ARM	Age Related Maculopathy
ARPA	Automatic Radar Plotting Aid
Cd/m^2	Candelas per metre square
COLREGS	International Regulations for Preventing Collisions at Sea
DAC	Dark Adaptation Curve
ECDIS	Electronic Charts Display and Information System
GMDSS	Global Maritime Distress and Safety System
gt	Gross tons (measurement of volume)
IBS	Integrated Bridge System
IMO	International Maritime Organization
LMC	Lairdside Maritime Centre
MAIB	Marine Accident Investigation Branch
MCA	Maritime and Coastguard Agency
MSN	Merchant Shipping Notice
NVQ	National Vocational Qualification
OOW	Officer of the Watch
RoPax	Roll on-roll off and passenger ferry (Ship classification)
SOLAS	Safety of Life at Sea
STCW 78	Standards of Training, Certification and Watchkeeping regulations
STCW Code	Standards of Training, Certification and Watchkeeping code of practice
VHF	Very High Frequency (radio)
VTS	Vessel Traffic Services