LIGHT, VISION AND THE WELFARE OF POULTRY

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Abstract

The visual system of domestic poultry evolved in natural light environments, which differ in many respects from the artificial light provided in poultry houses. Current lighting systems are designed mainly around human vision and poultry production, ignoring the requirements of poultry vision and the functional development of visual abilities during rearing. A poor correlation between the light provided and that required for effective vision may influence visually mediated behaviours such as feeding and social interaction, leading to distress and poor welfare. To understand fully the impact of the light environment on the behaviour and welfare of domestic poultry we need (i) to measure the physical properties of the light environment in a standard and relevant manner; (ii) to identify the limits of visual abilities in various light environments; (iii) to determine how light environments during rearing may disrupt the functional development of vision; and (iv) to resolve how visual abilities and lighting interact to affect visually mediated behaviour. Some conclusions can be drawn about the impact of current lighting regimes on bird welfare but there remains a pressing need to resolve various issues in this interaction. We propose, first, that dark periods should have a minimum duration of six hours; second, that bright light should be used in cases where pecking damage and cannibalism do not pose a problem; and third, that it is unlikely that the 100 Hz flicker associated with fluorescent light can be perceived by poultry. With less certainty, we can suggest that ultraviolet-supplemented lighting may have some welfare benefits, and that very dim lighting may adversely affect ocular development. We can only speculate on other issues, such as preferences and motivations for different coloured lighting or the ways in which lighting affects recognition of conspecifics. Several organisations and authorities have issued guidelines for poultry house lighting that strive to safeguard welfare and that are consistent with our current, but limited, understanding. One omission is a standard system for measuring light levels in poultry houses. Illumination with natural daylight would be an ideal solution to many lighting problems. Although some systems require artificial lighting for production purposes, we argue that it may be possible to rear birds humanely in artificial environments that contain some features of natural light. These features should be those for which poultry show some motivation, or whose exclusion would damage visual development.

Keywords: *animal welfare, behaviour, domestic poultry, environment, light, vision*

Introduction

Vision is probably the dominant sense in domestic poultry, the visual systems of which evolved in the distinctive light environment of the Asiatic jungle in the case of fowl and the North American plains in the case of turkeys; the wild mallard, from which most domestic ducks are derived, is found in many parts of the world. Natural light comprises two components: direct sunlight and diffuse light reflected from clouds and other surfaces. The colour and irradiance of light under a jungle canopy vary both diurnally and seasonally and depend on the density and spectral characteristics of the vegetation, amongst other things. Endler (1993) characterised the light environment within forests and showed how it may affect an animal's or plant's appearance. The co-evolution of vision and visual signals was determined, in part, by the natural light available to animals.

In modern poultry houses, the design of lighting systems is largely based on human vision and must meet criteria for production and inspection. Whereas we now have a good understanding of how lighting regimes (in particular photoperiod) affect poultry reproduction and production, our knowledge of their visual abilities and of the involvement of these abilities in key behaviours such as social recognition and feeding is poor by comparison. Our thesis is quite simple: the light environment in poultry houses should permit the development of normal vision and allow poultry to see well enough to carry out critical visual tasks. In this review, we describe the basic physics necessary to understand the nature of the light environment of poultry houses, we determine the limits of our understanding of key visual abilities, we suggest areas in which information is scant, and we draw conclusions about the nature of a lighting system that satisfies physiological, behavioural and production criteria.

Measuring light environments

Physics and terminology

Radiometry describes a system of light measurement rooted in common physical power and energy units which is independent of the sensory sensitivity of the observer (eg a hen or human). Photometry, on the other hand, adapts radiometric measures based upon the particular species-specific sensory sensitivity of the observer, and consequently these are more commonly used when the biological effects of light on organisms are considered. Table 1 lists some commonly used radiometric measures and their photometric equivalents.

Table 1 Commonly used radiometric units and their photometric equivalents.

Radiometric quantity		**Photometric quantity**	
Radiant energy	J	Luminous energy	lm s
Radiant flux	J/s or W	Luminous flux	lm
Radiant emittance	W/m^2	Luminous emittance	lm/m^2 or lx
Irradiance	W/m^2	Illuminance	lm/m^2 or lx
Radiant intensity	W/sr	Luminous intensity	lm/sr or cd
Radiance	W/sr/m^2	Luminance	cd/m^2

cd, candela; J, Joule; lm, lumen; lx, lux; sr, steradian; W, Watt.

The basic quantity in the science of radiometry is radiant flux, which describes the amount of radiant energy emitted per second from a luminaire (light source). Radiant flux is measured in Watts (W); it can be directly determined with a radiometer as a single value, or with a spectroradiometer as values at particular wavelengths to give a spectral power distribution. Typical spectroradiometric power-distribution measurements taken in natural and artificial environments are shown in Figure 1. The radiant flux incident upon a surface per unit area (W m^{-2}) is called irradiance. The reduction in the irradiance upon a surface as the distance between it and the source increases is described by the inverse square law (see Appendix, equation 1).

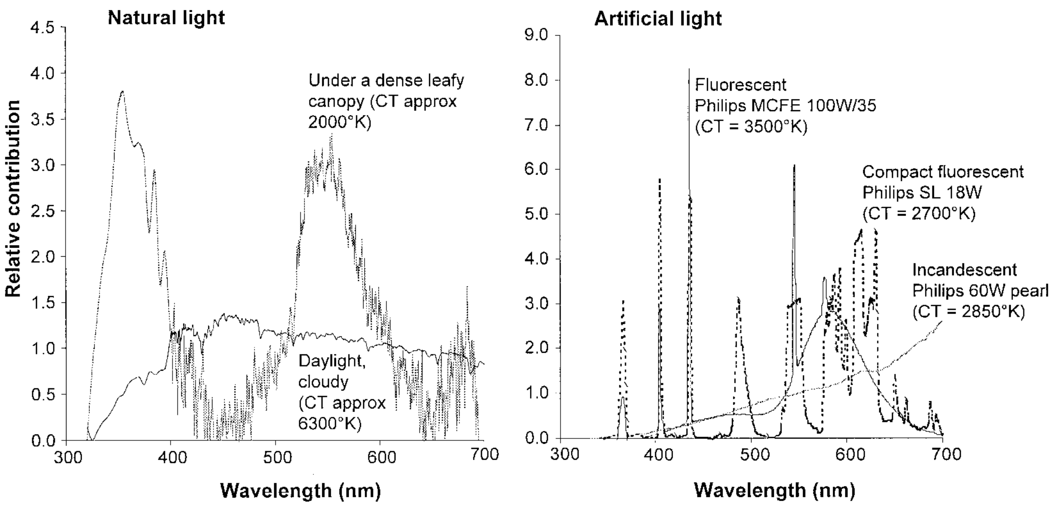

Figure 1 **Comparison of the relative spectral power distribution of natural and artificial illumination (all at equal total irradiance) measured with a spectroradiometer and indicating colour temperature (CT).**

Converting the radiometric measures shown in Table 1 to their photometric partners is achieved by weighting the radiant quantity by the sensory sensitivity of the human; it is generally accepted that photometric quantities relate more closely to actual brightness perception than radiometric quantities. Luminous flux (lm), a photometric measure equivalent to radiant flux, is calculated by multiplying the value of the luminaire's radiant flux at particular wavelengths by the corresponding human spectral sensitivity at those same wavelengths (shown in Figure 2; see later. See Appendix for the equation for the derivation of luminous flux). The photometric equivalent of irradiance is illuminance ($lm\ m^{-2}$) or lux (lx). An analogous set of photometric quantities could be derived for an animal by replacing the human spectral sensitivity curve with that specific to the animal. As with irradiance, as the distance between the surface and the source increases, the decrease in illuminance obeys the inverse square law.

Luminaires such as those in Figure 1, which are all nominally 'white' light sources, can be classified using the concept of black body absolute temperature (see Appendix, equation 2). This offers a useful way of specifying a single number which indicates the colour characteristics of white luminaires. This is achieved by finding the black body radiant emittance curve that most closely resembles that of the white luminaire curve. The temperature associated with the chosen black body curve can then be cited as the colour temperature of the luminaire. This provides a useful means of classifying luminaires which may all be qualitatively described as white, but which differ in their actual appearance. Table 2 gives the colour temperature of a range of white luminaires.

Describing the light environment of poultry houses

Many poultry houses are environmentally controlled with light provided via artificial luminaires and little, if any, natural daylight. Fluorescent luminaires are often used because of their superior energy efficiency and longer life. They are preferred to incandescent luminaires, much of whose radiant energy is emitted as infra-red wavelengths ($\lambda > 760$nm) and therefore invisible. By comparison, a Philips 60W pearl incandescent lamp (see Figure 1) generates 11.8 $lm\ W^{-1}$ compared with 85 $lm\ W^{-1}$ for a Philips MCFE 100W/35 conventional

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fluorescent luminaire (Philips 1997). Compact fluorescent luminaires are also popular because of their ease of installation, and some can be retro-fitted into incandescent screw-fit or bayonet cap lamp holders. Other costs, however, ameliorate the efficiency advantage of fluorescent-type luminaires including their higher initial installation costs and the expense of dimming control units.

Artificial light in poultry houses is of a different quality to natural daylight (eg in jungles and plains), which we presume is optimal for the efficient operation of the visual system of fowl and turkeys. The first major difference is that poultry houses are usually very dimly lit. Typically, turkey houses are illuminated to between 1 lx and 5 lx, and broiler and hen houses to between 5 lx and 30 lx. These low illuminances are provided largely to control pecking damage and cannibalism that is associated with brighter illuminances, but also to reduce energy costs. The variation in illuminance around a poultry house may also be large, eg between 1 lx and 200 lx in a caged hen house, depending on the distance of the cage from the light sources (Prescott & Wathes 1999a). Table 3 gives the illuminances typically encountered in various light environments.

Second, the photoperiod may be very different to that encountered naturally. For a few days after placement, illuminances are relatively high and the photoperiod is often 24h L : 0h D. Gradually over the next few weeks, the photoperiod may be changed to incorporate a longer dark period, and the illuminance reduced. Meat species of poultry may experience a range of photoperiods varying between no dark period, very short periods of

Table 2 **The colour temperature of a range of light sources.**

Source	Colour temperature (°K)
Northern sky light	7500
Average daylight	6500
*'Cool white' fluorescent lamp**	4300
*'Warm white' fluorescent lamp**	3000
Domestic tungsten lamp	2850
*Compact fluorescent lamp**	2700
Sunlight at sunset	2000
Candle flame	1800

* Colour temperatures will vary widely between manufacturers and in response to the colour characteristics of the phosphor mixes.

Table 3 **Comparative illuminance levels.**

Location	Illuminance (lx)
Direct sun	100,000
Overcast sky	1,000
Business office	250
Laying hen house[a]	≈20
Good street lighting	20
Twilight	10
Broiler house[a]	≈3
Turkey house[b]	≈2
Overcast night	0.0001

[a] Prescott & Wathes 1999a
[b] FAWC 1995

perhaps 1 h, or long periods of around 8 h. The shortest dark periods have no complement in the natural environment of most poultry species. In addition, dark periods in poultry houses are usually devoid of all light, whereas in natural environments there is usually some very low ambient lighting at night from the moon or stars. Laying species, including those kept for breeding purposes, experience more natural photoperiods with long dark periods. Changes in the light:dark ratio are used to initiate sexual activity and commencement of laying. A variety of intermittent lighting systems also exist which provide more than one, and sometimes many, dark periods in every 24 h. The effects of these lighting systems on poultry production have been reviewed by Buyse *et al* (1996) and Lewis and Perry (1995). Dawn and dusk periods are sometimes incorporated into lighting programmes either by using sophisticated dimming systems or by slightly offsetting the on/off timer controls on independent banks of luminaires. The reasons given for adopting these systems are usually that they represent a more 'natural' environment and allow the birds time to prepare for periods of darkness, perhaps by taking a meal.

The third difference between natural and artificial light is that the colour temperature of artificial luminaires differs markedly from that of natural daylight and also between incandescent and fluorescent sources, as shown in Figure 1. Other light sources, such as high-pressure sodium lamps, produce a narrower range of wavelengths although these are not widely used in poultry houses.

Finally, conventional fluorescent luminaires flicker at twice the frequency of the electrical supply duty-cycle (100 Hz in Europe; 120 Hz in the USA and Canada), and this flicker may be perceived by poultry. In the last few years, some producers have fitted high-frequency fluorescent luminaire circuitry, causing the luminaires to flicker at many kHz. These systems may be retro-fitted to poultry houses depending on the fluorescent lighting system, and some are claimed to offer superior energy efficiency.

Visual abilities of domestic poultry and their interaction with lighting

The effects of lighting on the behaviour and welfare of poultry are mediated predominantly by vision, although other non-visual photoreceptors such as the pineal gland or skin will also exert some influence. While the gross features of the avian visual system are similar to those of mammals, various subtle differences mean that their visual perception is different and often superior to that of humans. Only a few of the myriad visual adaptations that birds possess are critical to our discussion of the visual consequences of commercial lighting practises in poultry houses. In our opinion, the four most important visual abilities are spectral and flicker sensitivities, accommodation, and acuity, because these will illustrate in gross terms how poultry perceive their visual environment and consequently how light may affect visually mediated behaviours such as conspecific recognition. Other abilities may also be relevant but of lesser importance — for example, the ability to perceive polarised light. The following discussion of these four abilities in poultry concentrates largely on domestic fowl, as little has been reported on the vision of turkeys or other minority poultry species.

Spectral sensitivity

Domestic fowl have a number of adaptations to their colour-perception apparatus that are not shared by humans. First, they possess three types of photoreceptor, in comparison with just the rods and cones possessed by humans (King-Smith 1971). The additional type of photoreceptor is a double cone, the function of which is unclear although it does respond to incident light. Second, fowl have four photoreactive pigments associated with cone cells, which are responsible for photopic colour vision (Yoshizawa 1992), compared with three in humans; these are maximally sensitive at wavelengths of 415, 455, 508 and 571 nm, versus 419, 531 and 558 nm in humans (Dartnall *et al* 1983). Third, fowl possess coloured oil droplets in their cone cells, which filter incident light before it reaches the photoreactive pigments. The droplets are associated variously with individual cone cell types (Bowmaker & Knowles 1977). Turkeys have similar colour perception apparatus (Hart *et al* 1999). The spectral sensitivity curves derived for fowl by Prescott and Wathes (1999b) using a behavioural test, and by Wortel *et al* (1987) using an electrophysiological test, differ from those of humans: the relative response is broader in fowl, and ultra-violet A radiation (UV_A; $320 < \lambda < 400$ nm) can be perceived. These curves are compared in Figure 2. The overall effect of these anatomical differences in the fowl is a visual system that is well adapted to collecting spectral information. However, the penalty may be that a high illuminance is required for the system to work at its full potential.

The implications of the fowl's spectral sensitivity are threefold. First, the unit with which we have traditionally measured illuminance in poultry houses, the lux, is inaccurate. For animals such as poultry, which possess different spectral sensitivities to humans, the lux unit will not correlate well with the perceived brightness of different light sources, since the lux is based on human spectral sensitivity (see Appendix, equation 3). Using the traditional view that brightness perception is based upon the sum of the individual cone responses, we calculate that for typical fluorescent and incandescent luminaires illuminated to the same lux level — and, consequently, isoluminant for humans — fowl would perceive the incandescent bulb as approximately 20% brighter than the fluorescent tube. Alternative units for measuring fowl-perceived illuminance, the so-called 'clux' or 'galluminance', have been derived by Prescott and Wathes (1999b) and Nuboer *et al* (1992a), respectively. It may be that the double cone has a more prominent role in luminance perception, although this novel theory requires further proof (Osorio *et al* 1999). Within species, the link between measured illuminance and perceived brightness is presumed to be approximately linear. However, because additional factors relating to the perception of brightness may be involved in different species, it is not possible with these data to compare perceived brightness between fowls and humans for a particular light environment.

Second, the range of available wavelengths emitted from luminaires may constrain the flow of colour-mediated information. For example, if some social information is imparted by the redness of another bird's comb, such as its fitness as a mate, then a fluorescent light that emits little red light will hinder the transmission of this visual cue. An incandescent luminaire, however, will allow the information to be transmitted super-efficiently since it contains an abundance of red light. Equally important for some species (eg the rabbit, Nuboer *et al* 1983), the diurnal variation in the colour temperature of daylight can synchronise behaviour patterns independent of changes in illuminance.

Third, artificial luminaires produce little, if any, UV_A radiation which is biologically relevant in poultry species. Its inclusion in conventional lighting, with other measures, can help control feather pecking in turkey stags (Lewis *et al* 2000) and can mediate mating behaviour and mate choice in broiler breeder fowl (Jones *et al* 2001). There may also be a role for UV_A radiation in duck production, given that the mallard is sensitive to wavelengths as low as 340 nm (Parrish *et al* 1981).

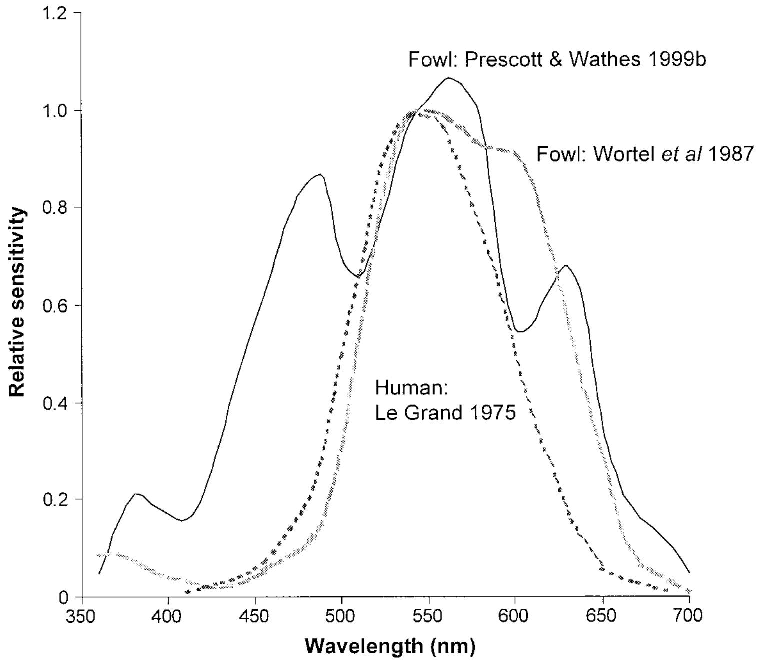

Figure 2 **Relative spectral sensitivities for fowls and humans, normalised to sensitivity at 550nm.**

Flicker sensitivity

Flicker sensitivity is less well understood than spectral sensitivity. Both conventional and compact fluorescent luminaires flicker at either 100 Hz or 120 Hz in Europe or North America, respectively. The light flux change is approximately sinusoidal in response to the alternating current (AC) supply, but often becomes progressively less symmetrical as the luminaire is dimmed, which is possible for all conventional but only some compact luminaires.

Using a psychophysical method, Nuboer *et al* (1992b) found that some fowl may be able to perceive blue light ($\lambda \approx 476$ nm) flickering up to 105 Hz, but are less sensitive for other colours (maximum sensitivity for ultraviolet [370 nm] = 70 Hz; indigo [430 nm] = 75 Hz; green [556 nm] = 95 Hz; and red [670 nm] = 85 Hz). Also, flicker from a white compact fluorescent luminaire at 80 Hz was perceived, but higher flicker rates were not tested. The maximum frequencies perceived by humans are generally quoted in the range 50–60 Hz (Brundrett 1974). However, flicker sensitivity in humans depends critically on two factors. First, flicker is perceived better at higher than at lower mean illuminance. Second, flicker with high modulation (a measure of the magnitude of illuminance-change through a flicker cycle [see Appendix, equation 4]) is better perceived than flicker with low modulation (De Lange 1958). The conventional Philips fluorescent and compact-fluorescent luminaires mentioned previously and shown in Figure 1 possess flicker modulation depths of 23% and 39%, respectively. The sensitivity to changing modulation was not characterised by Nuboer *et al* (1992b) who used a single value of 95%. In a recent study, Jarvis *et al* (2002) found that poultry cannot detect 100 Hz flicker of white light at 100 lx, but may be able to at very much higher illuminances. In a tightly controlled experiment, Boshouwers and Nicaise (1992) found that, at an illuminance of 90 lx, broilers exposed to 100 Hz flicker exhibited less ‘activity’ than control birds exposed to flicker at 26 kHz. This finding is contrary to the work of Jarvis *et al* (2002), but may reflect supra-threshold effects, significant deviations from sine-wave flicker or some other effect. At an illuminance of approximately 14 lx, however, Widowski and Duncan (1996) found that laying hens had no preference for fluorescent light flickering at low (120 Hz) or high frequency (20–60 kHz). In less controlled but nevertheless useful studies, Widowski *et al* (1992) and Sherwin (1999) found that hens preferred fluorescent luminaires, flickering at 120 Hz and 100 Hz and illuminated to approximately 12 lx and 10 lx, respectively, over incandescent luminaires; however, both authors commented that colour temperature and illuminance were confounded between their treatments. In addition, the illuminance and modulation depths for these fluorescent luminaires may have been so low as to preclude the perception of flicker by the birds. From the information available, we see no reason to recommend a change from low- to high-frequency fluorescent lighting with respect to the bird's comfort for two reasons. First, hens have no sensitivity to 100 Hz flicker at the illuminances and modulation depths typically found commercially; and second, three out of four preference tests showed no evidence of aversion, and the interpretation of the remaining test is unclear.

Accommodation

In order to focus images on the retina, the eye must refract light rays. A greater degree of refraction is necessary to view near objects than to view objects far away. The degree to which an eye can adjust its refractive power is called the accommodative range (usually measured in dioptres, D). In poultry, because the eye is relatively small and the viewing distance is often very short (between 50 mm and 60 mm for laying hens during foraging), the refraction of the eye must be very powerful if the image is to be clearly focussed upon the retina. This may be facilitated by two mechanisms. The lens can thicken by the action of 'Brücke's' portion of the ciliary muscles, also possessed by humans, and this accounts for around an 8 D change in refractive power. The cornea can also bulge under the action of 'Crampton's' portion of the ciliary muscle, increasing the refractive power by a further 8 D (fowl: Schaeffel & Howland 1987; humans: Pugh 1988, Wyszecki & Stiles 1982). Overall, the refractive power of an unaccommodated fowl eye (ie looking at an object far away) is approximately 80 D, compared with 60 D in humans. Fowl are capable of much stronger refraction of around 96 D when focussing at their near point (the nearest point to the eye at which an object can still be seen in focus), compared with approximately 68 D for humans. Ducks, which naturally forage underwater, can change their refractive power by up to 50 D compared with 16 D and 8 D for fowl and humans, respectively. This is necessary because the powerful refraction resulting from the air–cornea boundary is lost underwater; for this same reason, non-aquatic mammals such as humans cannot focus well underwater (Sillman 1973).

In fowl, accommodative range is probably enhanced by lower-field myopia, which allows objects in this field (such as potential food items in the ground-horizon) to be focussed upon the retina at small viewing distances, while simultaneously, objects further away (such as potential predators) are focussed in the upper visual field (Schaeffel *et al* 1994). This effect amounts to a difference between lower- and upper-field refractive power of around 8 D for six-day-old chicks, declining to around 4 D for 28-day-old birds.

The interaction between lighting and accommodation is important because light stimulation during rearing can affect the ability of the eye to accommodate. As animals grow, their eyes also enlarge which means that their refractive power must also change if emmetropia (the absence of refractive error) is to be maintained. One theory suggests that ocular elongation is regulated by diurnal rhythms, perhaps mediated through the retinal neuromodulator dopamine (Nickla *et al* 1998). Constant light (approximately 700 lx) causes refractive errors to appear in growing broilers after three days of age, resulting in a 15 D difference between these and control birds by 78 days (Li *et al* 1995). After two months, all the experimental birds had developed cataracts, and many showed retinal damage including tears and loss of the cone oil droplets. Stone *et al* (1995) showed that two strains of White Leghorn chicks developed slightly different degrees of refractive error in response to photoperiod. By interpolation, one strain, 'Cornell K' chicks, appeared to develop small errors after two weeks when the light period exceeded around 18 h out of 24 h, whereas 'Truslow' chicks only displayed refractive errors at two weeks when the light period exceeded 23 h. Illuminance may also affect the morphology of turkeys' eyes (Thompson & Forbes 1999). Turkeys kept under 2 lx had significantly enlarged globes, amongst other effects, compared with those housed under 50 lx. This is evidence of buphthalmus and probably accounts for the reports of 'turkey blindness' syndrome sometimes found in commercial flocks (Ashton *et al* 1973). Clearly, poultry reared in conditions that could induce refractive error will be less able to extract important visual information from their surroundings. For example, they may be unable to navigate around a large poultry shed or to recognise a threat in time to take evasive action. Equally, rearing environments that induce abnormal sensory development or damage are ethically questionable. While it may not be possible to reduce the potential effects of dim lighting on eye development without increasing pecking damage and cannibalism in some species, it is possible to increase the length of the dark period available to poultry with only minimal effect on productivity. With broilers and some varieties of duck where feather pecking and cannibalism are not a significant problem, it should be possible to use bright lighting.

Spatial acuity

Acuity is a measure of spatial resolution or the level of detail detected in visual images. This is determined largely by the optical clarity and precision of the optical system and the density of rod and cone cells in the retina. Acuity falls rapidly once the far and near limits of accommodation are exceeded. Gratings are often used to measure acuity, with the resolution limit defined as the minimum grating fineness which can just be distinguished from an isoluminant, uniform grey stimulus; the unit of measurement is the number of 'bars' or 'cycles' per degree of visual angle. Spatial acuity is also dependent upon two other parameters: luminance of the stimulus (L, measured in cd m^{-2}) and contrast (C, %) between the light and dark bars. In fowl, acuity has been measured variously as 1.5 cycles/degree (L = 39 cd m^{-2}, C = 80%; Over & Moore 1981), 4–6 cycles/degree (L = 2.7 cd m^{-2}, C = 93–100%; DeMello *et al* 1992) or 7 cycles/degree (L = 12.1 cd m^{-2}, C = unknown; calculated by DeMello *et al* 1992 from Johnsen 1914). Fowl acuity is poorer than human acuity, which was measured at 30 cycles/degree by Spence (1934). Variations between the results of investigators may result from differences in the stimulus luminance and/or contrast. In crude terms, an acuity of 30 cycles/degree viewed at the human near point (approximately 12.5 cm away from the eye) would allow black dots of 70 μm in diameter, and separated by 70 μm, to be resolved against a light background. An acuity of 5 cycles/degree seen at a chicken's near point (assumed to be approximately 5 cm) would allow a similarly presented line of dots of 170 μm in diameter to be resolved. The two- or three-fold higher human acuity at the near point may reflect the action of the specialised fovea in humans. However, acuity falls rapidly as distance from the fovea increases: 5° from the centre of the fovea acuity declines by 50%, and at 30° by more than 90% (Coren *et al* 1979). Fowl also possess an area of high cone-cell density, or an 'area centralis' (Morris 1982), which probably serves as a region specialised in discerning detail, although it is less specialised than the fovea. This area centralis has two extensions (determined by mapping the subserving retinal ganglion cells;

Ehrlich 1981). The central extension receives images from just above the central point of that eye's hemispheric field of view (the central field). The lateral extension extends from this area, receiving images in a band or stripe running slightly downwards towards the beak (into the infero-frontal field). The central extension may be used for detailed imaging of objects in the upper visual field, such as potential predators, while the lateral extension may be used to image objects in the lower myopic field, such as food and small prey (Ehrlich 1981). The limited reduction in ganglion-cell density with increasing eccentricity from this region implies a less severe reduction in acuity than that encountered in humans. Also, because of the shape of the fowl's eyeball, which is flattened in comparison with that of the human, all images are equally well focussed upon the retina. In humans, images focussed on the fovea cause the rest of the field of view to become defocussed (King-Smith 1971). This may mean that although the maximum spatial acuity is very much higher for humans than for fowl, the mean spatial acuity around the whole field of view may be similar for the two species or even higher for chickens.

The need for light

We can assume that vision is an important sense for poultry given the size, placement and prominence of their eyes and the proportion of the avian brain devoted to visual processing (Güntürkün *et al* 1989). In the progenitor species of poultry, vision was presumably adapted to the range of light environments that prevailed in their natural habitats. Both the spectral composition and illuminance in these habitats would have affected the availability and quality of visual information about the location and type of food, the identity and intent of conspecifics, the detection of predators, and cues for navigation and territorial recognition. When poultry are housed indoors, the relative importance of this information changes. First, recognition of another bird's intent or status rather than its identity is potentially more useful within a large flock if futile aggression is to be avoided. Second, the unnaturally large flocks that are closely confined in buildings lacking readily identifiable visual cues may mean that social groups within distinct territories can be established only with difficulty, even if they are desirable or necessary. Third, the numerously placed food and water sources aid the location of these sources. Thus, the design criteria for the light environment of poultry houses should be based upon the problems arising from large-scale husbandry rather than the requirements of small flocks of wild poultry. It is not necessary to recreate the light environment of a jungle clearing. In fact, we need to include only those criteria for which fowl show a certain level of motivation or those that are essential for normal eye development. In this way, the light environment of a poultry house may still cater for the visual, behavioural and welfare needs of poultry, despite differing from natural daylight. This takes advantage of the control allowed by artificial lighting, while incorporating the benefits of particular aspects of daylight which poultry require for normal visual perception. Clearly, if the necessity for control of the light environment for production, welfare or economic reasons can be removed, then we would advocate the use of natural daylight, which would obviate the dilemmas caused by artificial lighting.

The requirements of poultry for light can be deduced from observation of the birds' preference and motivation for specific features of the light environment. A list of potentially significant experimental findings relating to lighting parameters is given in Table 4. However, with these few exceptions, we know comparatively little about the innate preferences of poultry for light or the reasons underlying their choices. We can conclude that for turkeys and perhaps other poultry species, UV_A-supplemented light may be beneficial; it has a role in mating, it is preferred by turkeys, and work by Lewis *et al* (2000) has also indicated a role in reducing pecking damage. We can also conclude that for layer and broiler chicks, the initial preference for bright light weakens with age, and this preference is attributable only to a change in the preference for resting in bright light when young and in dim light when older. This implies the need for spatially or temporally variable illuminance in poultry houses. Finally, for laying hens and turkeys, fluorescent light is preferred to incandescent light (notwithstanding differences in perceived illuminance). We know little, however, about the strength of motivation underlying these preferences, and the preferences and motivations for colour and colour temperature are not clearly understood. D'eath and Stone (1999) indicated that recognition of familiar from unfamiliar laying hens on the basis of feeding preferences and aggressive interactions was possible under bright white light (77 lx) but not dim white light (5.5 lx), and recognition was not possible under red or blue light at either illuminance.

New lighting systems for poultry houses — a way forward

In the United Kingdom, guidelines for poultry production are imposed or recommended by welfare organisations such as the Royal Society for the Prevention of Cruelty to Animals (RSPCA), the Farm Animal Welfare Council (FAWC), major supermarket retailers, and the UK government's Department for the Environment, Food and Rural Affairs (DEFRA, formerly the Ministry of Agriculture, Fisheries and Food; Table 5). There is a clear requirement for these recommendations and they represent our best current understanding. Manser (1996) provides a comprehensive review of the available literature and many of her recommendations are reflected in the current RSPCA guidelines. Many of FAWC's recommendations on lighting are presented as interim measures pending future research.

These guidelines also belie a more fundamental problem, which is that measurement of light environments in poultry houses is not standardised; in our experience, many poultry units do not even possess a serviceable light meter. In order for the guidelines to achieve their aims, it is imperative that we first adopt a measurement method that is quick, accurate and easy to use. For measuring illuminance, we recommend that the use of light meters becomes more common; ideally, one should be available to all poultry units. As with all measuring instruments, the light meter should be clean, undamaged and regularly calibrated. Given that light meters can be purchased cheaply, this should not pose a significant burden to the poultry industry. When surveying the light environment of a poultry house, it is important to take a sufficient number of measurements to reflect the variation in illuminance around the building, and standard methods exist (for example, see IES 1966). In most houses where the lights are of uniform type, similarly aged and regularly spaced, it is necessary only to sample a limited number of transects across the house directly below and between rows of lights (eg Prescott & Wathes 1999a). In units where birds are housed at different heights, such as caged layers, it is essential that the illuminance at each location is recorded. In units where the light sources are of non-uniform type, differently aged or irregularly located, more readings will need to be taken to reflect this variability. The orientation of the light meter sensor is also important. For human purposes, the orientation of the light meter should be normal to the plane of the surface that will be used (British Standards 1985). By way of example, this will mean that the sensor is held horizontally close above an office desk's surface, but for a design office's drawing board, the sensor will be inclined from the horizontal at the angle of the drawing board surface. This means that measurement of illuminance, and presumably to a great extent the subjective assessment of the quality of illuminance, is specific to the orientation of the particular visual task being conducted.

In research into lighting for poultry, two methods are described for orientating the sensor-head. In the first, the head is held horizontally (eg Kjaer & Vestergaard 1999; Moinard *et al* 2001) and in the second, the head is angled in the direction of maximum illuminance — which is usually in the direction of the nearest lamp (Lewis *et al* 1999; Prescott & Wathes 1999a); the majority of papers, however, omit these details. The difference in the measurement can be significant. For example, in a room illuminated by a single incandescent bulb, at a position on the floor 1.5 m away from the point directly beneath the lamp, we obtained a reading of 74 lx with a light sensor held horizontally, which increased to 114 lx when the sensor was angled in the direction of maximum illuminance. It is imperative that a defined procedure for orientating the sensor head is agreed upon when measuring light in poultry houses or for the purpose of experiments. The Standing Committee of the European Convention on the Protection of Animals Kept for Farming Purposes suggests that illuminance should be measured in three planes at right angles to each other, although the rationale is not given (Council of Europe 1995).

Table 4 Significant choices for various lighting parameters.

Species	Choice/task	Preference	Reference
Laying hens	Operant task to turn lights on and off.	Preferred light to dark, not prepared to work hard for dark.	Savory & Duncan 1982/83
	Compact fluorescent vs incandescent.	Preferred the fluorescent environment.	Widowski *et al* 1992*
	High frequency vs low frequency fluorescent.	No preference.	Widowski & Duncan 1996
	Eating in 6, 20, 60 or 200 lx.	Preferred to eat in 200 lx.	Prescott & Wathes 2002
	Nest box illuminated by 40 or 5 lx for two strains at two ages.	Only White Leghorns laying their first egg showed preference for dimmest nest box.	Appleby *et al* 1984
	High pressure sodium lamps (426 lx) or incandescent lamps (27 lx).	No overall preference, some variation in the distribution of behaviour.	Vandenberg & Widowski 2000*
	6, 20, 60 or 200 lx environments.	Preferred to rest in brightest light at 2 weeks and dimmest at 6 weeks. Active behaviours performed preferentially in brightest environment.	Davis *et al* 1999
Broilers	Gradient of illuminance.	Preferred bright light (20–25 lx) at 1 day old; declined to 10–15 lx by 14 days old.	Alsam & Wathes 1991
	Red, green, blue or white light.	Preferred green and blue to red and white.	Prayitno *et al* 1997*
	20 or 0.05 lx environments.	Preferred 20 lx when young but increasing use of 0.05 lx after 4 weeks old.	Berk 1995
	6, 20, 60 or 200 lx environments.	Preferred to rest in 200 lx at 2 weeks and 6 lx at 6 weeks. Active behaviours performed preferentially in 200 lx.	Davis *et al* 1999
	Choice of incandescent, spectral sensitivity match, warm white or 'daylight' fluorescent.	No preference at 1 week old but at 5 weeks old preferred 'daylight' and warm white fluorescent.	Kristensen *et al* 2002
	Operant task to turn lights on and off.	Preferred light to dark, not prepared to work hard for dark.	Savory & Duncan 1982/83
Turkeys	Fluorescent light with or without UV_A.	Preferred fluorescent light with UV_A supplementation.	Moinard & Sherwin 1999*
	4 or 12 lx.	Preferred 12 lx.	Sherwin 1998
	Compact fluorescent or incandescent.	Preferred fluorescent environment.	Sherwin 1999
	Nest boxes illuminated to 650–1000, 50–150 or 0.5 lx.	Avoided the 650–1000 lx nest boxes.	Millam 1987
	Choice of dark, 6, 20 or 200 lx environments.	At 2 weeks old, all behaviours preferentially performed in 200 lx environment. At 6 weeks old, resting behaviours expressed in 6, 20 and 200 lx environments.	Barber *et al* in press
Ducks	Choice of dark, 6, 20 or 200 lx environments	At 2 weeks old, locomotion and environmentally directed pecking — and, at 6 weeks old, resting and perching — occurred most often in 6, 20 and 200 lx.	Barber *et al* in press

* Indicates a significant potential for illuminance, colour or flicker interactive/confounding effect.

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Table 5 Examples of regulations/guidance relating to lighting poultry species and other salient comments.

Source	Poultry type	Minimum illuminance	Photoperiod		Dawn/dusk dimming	Comments
			Light	Dark		
EU	*All*[1]		Must not be kept in darkness.	*'...an appropriate period of rest from artificial lighting...'*	—	
	Laying hens[2]	*'Sufficient to allow all hens to see one another and be seen clearly, to investigate their surroundings visually and to show normal levels of activity.'*		*'... about one third of a day ...'*	Yes	Where natural light is admitted it must be evenly distributed.
DEFRA	*Laying hens*[3]	5 lx for caged layers but 10 lx for other systems.	—	*'about one third of a day'*	Yes	Measured at feed trough level.
	Broilers[4]	10 lx (preferably 20 lx).	>8 h	*'A period of darkness (not less than 30 min) in each 24 h cycle'*	No	
	Turkeys[5]	Such that all stock can be clearly seen and inspected.	>8 h	*'A period of darkness in each 24 h cycle'*	No	
	Ducks[6]	Such that all stock can be clearly seen and inspected.	—	*'A period of reduced light intensity every 24 h'*	(see comments)	Dimmers should be used to avoid sudden changes in luminance.
Council of Europe	*Domestic fowl*[7]	20 lx		*'approximately one third of a day'*	Yes	Measured at bird eye level in three planes at right angles to each other.
	Turkeys[8]	10 lx		Around 8 h but greater than 4 h	Yes	As far as possible natural light should be provided.
RSPCA (Freedom Food)	*Laying hens and pullets*[9]	10 lx	>8 h	>6 h	Yes	Records of lighting patterns must be kept. Patches of high light intensity should be avoided.
	Broilers[10]	20 lx	>8 h	>6 h but <12 h	Yes	
	Turkeys[11]	20 lx	>8 h	>6 h	Yes	
	Ducks[12]	20 lx	>8 h	>6 h	Yes	
FAWC	*Layers*[13]	5 lx (pref >10 lx)	—	—	—	Measured at feed-trough level for cages or at bird height for other systems.
	Layers (colony systems)[14]	10 lx	>8 hrs	*'adequate period'*	Yes	Minimum throughout the entire house.
	Broilers[15]	10 lx (pref >20 lx)	—	>30 min	—	Patches of bright light to be avoided. Uniform distribution.
	Broiler breeders[16]	Initially >60 lx falling to >10 lx by day 10. >10 lx up to point of lay. >20 lx during laying.	>8 hrs	>6 hrs	—	
	Turkeys (meat)[17]	5 lx	—	8 hrs	—	

[1]EU 1998; [2]EU 1999; [3]DEFRA 2002a; [4]DEFRA 2002b; [5]MAFF 1987a; [6]MAFF 1987b; [7]Council of Europe 1995; [8]Council of Europe 2001; [9]RSPCA 1999a; [10]RSPCA 1999b; [11]RSPCA 1999c; [12]RSPCA 1999d; [13]FAWC 1997; [14]FAWC 1991; [15]FAWC 1992; [16]FAWC 1998; [17]FAWC 1995.

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The guidelines are also ambitious in that they do not set any permitted error in the levels they suggest. For example and solely from our experience, a variation of ± 20% about the mean illuminance is probably achievable across 90% of the floor area by judicious arrangement of the luminaires. Various organisations offer design services which can predict the light spread around a building as a function of the type of lights and their distribution. However, as we have argued previously (Davis *et al* 1999), a spatially uniform light environment may not account for the preferences of the birds. We also believe that if use of a range of sources is permitted in poultry houses, then some account must be made for the difference in illuminance with which they will be perceived by the birds — perhaps by using the 'clux' or 'galluminance' units described previously.

On the basis of the available evidence, we propose that illuminance and other light parameters in a poultry house should (in no order of priority):

1) promote high levels of production and reproduction;
2) allow the development of normal vision and eye morphology during rearing;
3) satisfy preferences that are highly motivated; and
4) enable a bird to carry out those visually mediated behaviours that are consistent with good welfare.

These requirements may differ from normal commercial practice in which nominally white light of low illuminance is employed uniformly throughout a poultry house. Any new lighting system will also have to be cost effective.

Much of the information necessary to satisfy criterion 1 above is available in scientific reviews (eg Lewis & Morris 1998; Lewis & Perry 1995) and most poultry production textbooks. We still, however, have an incomplete understanding of whether and how lighting affects behaviour and welfare. Resolution of these criteria requires research. For criterion 2 we need to know how illuminance and photoperiod affect the normal development of vision, particularly accommodation and consequently acuity. These are only likely to affect adversely the welfare of poultry housed at the extremes, such as birds reared under more-or-less continual illumination or in very dim conditions, although these are both commonly encountered. Whether colour temperature and flicker characteristics affect the functional development of vision is probably less important. Even quite profound changes in the colour balance of rearing environments failed to generate abnormal spectral sensitivity in pigeons (Brenner *et al* 1983). For criterion 3 we know that poultry exhibit apparent preferences for certain lighting parameters (see Table 4); however, there is only one choice test showing a preference for colour temperature independent of illuminance (Kristensen *et al* 2002). Preferences tell us only about the qualitative motivations of poultry and not their quantification; in this area there is scant information. Clearly, those motivations which are weak, and which presumably matter little to the bird, will not need to be incorporated into new lighting systems. Criterion 4 relates to criterion 3, and requires a detailed understanding of the effect of lighting conditions on the birds' ability to recognise and interact competently with their environment. This may be tackled through an understanding of how lighting affects visual abilities and consequently how lighting may affect birds' ability to recognise accurately visual stimuli. For example, the reduction in acuity with falling illuminance will explain how spatial information is lost under dim lighting. Some information is known for the fowl but little is available for other poultry species, although the same four visual abilities will be important for them also. Before any recommendations are made, however, commercial-scale tests should be conducted to verify the findings from small-scale experiments.

Conclusions, recommendations and animal welfare implications

In order to specify a light environment in a poultry house that satisfies both welfare and production concerns, we need to integrate an understanding of the physical environment and some fundamental aspects of poultry vision with behaviour and welfare studies. In this way, we will be better able to explain known responses and to predict responses to novel environments. Past work has often been piecemeal, poorly controlled and descriptive. Understanding the physics of the light environment requires the application of well-known and well-established physical principles. Our understanding of vision is progressing; for example, we now understand colour perception and flicker sensitivity in the fowl, although we still need to know more about spatial acuity and the role of the light environment in the development of visual abilities, particularly ocular accommodation. It may also be necessary to understand visual features that have more secondary roles — for example, the possibility that poultry can perceive polarised light, and its role in behaviour and welfare.

On the basis of our current knowledge, we can make some recommendations. First, even though our information is limited, short dark periods (perhaps less than 6 h) should not be used beyond the first few days after hatching because of potentially adverse effects on ocular development. The economic effect of increasing the length of dark periods is likely to be small. Second, for those species for which pecking damage and cannibalism are of minor concern (such as non-aggressive duck breeds and to some degree broilers) we recommend that bright light environments are used and where possible, daylight — provided that adequate dark periods, or dark areas in which to rest, are provided. Third, there is little reason to believe that poultry can perceive the flicker from low-frequency fluorescent lights and there is no need, in terms of the comfort of the birds, to fit incandescent or high-frequency fluorescent systems.

With less certainty we can first suggest that providing lighting of variable illuminance around a poultry house may accord with their preferences for conducting 'active' and 'inactive' behaviours. Provided that the areas of different illuminance are large enough, we do not expect that this will increase the risk of smothering, which sometimes occurs in small pools of bright light. Second, there may be some advantage to providing UV_A-supplemented light. Third, light sources of restricted spectral power emissions may constrain the flow of important visual information such as social recognition.

We can only speculate about birds' preference for white lights of different colour temperatures or the motivation of poultry for different illuminances or colour temperatures. Equally, we know very little about how the light environment affects the recognition of objects, navigation around the poultry house, or levels of fear.

Despite this dearth of scientific information, various legislative, commercial and welfare organisations have attempted to define interim lighting parameters to safeguard the welfare of poultry in poultry houses. All require or recommend an increase in illuminance and length of dark period and, as such, these recommendations are sound given our current level of understanding. However, these endeavours are undermined by the lack of a standard method for measuring light environments in poultry houses or the inclusion of permitted variation.

Allowing birds access to natural light environments, either through free-range management or through the provision of windows in poultry houses, is desirable but may not be essential to satisfy both welfare and production requirements. These requirements could be satisfied by specifying desirable features of natural daylight and incorporating them into artificial lighting systems.

Appendix

Point source irradiance

For a point light source placed at an angle θ from the normal to a surface, the irradiance (I_r, W/m^2) of the surface is given by:

$$I_r = I.\cos\theta / r^2 \quad (1)$$

where I is radiant intensity (W steradian^{-1}) and r is the distance from the source to the surface.

Black body radiation

A black body is an ideal material of uniform temperature that perfectly absorbs all radiation incident upon it. For equal areas, it radiates more power than any other source operating at the same temperature. Its unique feature is that its radiation output is characterised solely by absolute temperature (°K). The relationship between black body radiant emittance and absolute temperature is given by Planck's law:

$$M_\lambda = c_1 \lambda^{-5} (e^{c_2 \lambda T} - 1)^{-1} \quad (2)$$

where M_λ is the radiant emittance per 1 µm waveband, λ is wavelength in nm, T is temperature in °K, and c_1 and c_2 are universal radiation constants (3.74×10^{-16} Wm^2 and 1.44×10^{-2} mK, respectively).

Derivation of luminous flux

The luminous flux perceived by an animal is the sum of the cone cell responses:

$$l = k \int R(\lambda) . V(\lambda)\, d\lambda \quad (3)$$

where l is the luminous flux (lm), R(λ) is the incident spectral radiant flux (W), and V(λ) is the relative luminous efficiency. The value of k, 683 lm W^{-1} for humans in photopic vision, is based on the finding that the intensity of a black body at the melting point of platinum (2046°K) is judged to be 60 times greater than that of the *standard candle*. This particular standard source has, by definition, a fixed luminous intensity of 1 lm steradian^{-1}.

Flicker modulation depth

$$m = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad or \quad \frac{I_{max} - I_{mean}}{I_{mean}} \quad (4)$$

where m = modulation depth varying between 0 (no temporal flux changes) and 1 (maximum temporal flux changes), I_{max} = maximum illuminance, I_{min} = minimum illuminance and I_{mean} = mean illuminance.

Both definitions are mathematically identical when the light flux modulation is a regular sine waveform. As the waveform becomes less regular the first definition is a more accurate measure of modulation depth.

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