Lighting for Pig Units

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Executive Summary

Abstract

The behaviour of the progenitor species of the pig and the anatomy and physiology of the porcine eye suggest that the domesticated pig is best adapted for dim levels of natural light. This knowledge can therefore be used to specify lighting for domesticated pigs kept either indoors or outdoors. In general, English law is based on sound scientific evidence.

Pigs use vision to discriminate between each other and select food containers, demonstrating that vision plays a role in everyday behaviours useful in commercial situations, and that correct lighting is important on pig units.

Pigs show some seasonal variation in reproductive success, with summer reduced fertility linked mainly to high temperatures, but with the potential to be affected by day length. In wild boar, decreasing daylengths stimulate reproductive behaviour, and a similar response has been reported in commercial pigs under experimental conditions. Stimulating puberty in boars by decreasing daylengths will also hasten the onset of boar taint; however lighting is a minor factor in this, with sire line traits of much higher impact. Piglets and weanling pigs may benefit from additional hours of light in order to locate food sources, but long term 24h light has proven detrimental effects on welfare for pigs of all ages and should be avoided. Keeping pigs in 24h dark has less detrimental effects than constant light, but still provides poorer welfare than a cyclical light: dark routine.

Current legislation on lighting is based on the ability of the stockkeeper to inspect animals, rather than the ability of the pigs to conduct visually oriented behaviours. There is limited evidence in the literature on the effects of spectra (coloured lights or colour balance of lights) on pig production. When red light has been used, it is likely to be perceived as dark by pigs. Dawn and dusk periods of phased illuminances have not been researched, but could provide helpful time cues to the pigs and could reduce the dazzle or confusion of rapid light change, and competition at timed feeders.

Current knowledge on flicker sensitivity suggests that the pig will have similar critical flicker fusion to the cat, and be unable to detect the flicker of correctly functioning fluorescent lights. Natural light differs in many respects from artificial light and few controlled studies have been published comparing these two sources. High levels of natural illuminance (including UV) are likely to cause sun burn and heat stroke in the pig, which must be given relief in the form of shade or wallows. Whilst pigs need natural light or UV to produce vitamin D3, deficiency of vitamin D is not considered to be a problem, and vitamin D2 is provided in a balanced diet.

This report highlights a number of areas where research onto the effects of lighting on pigs is insufficient for accurate conclusions to be drawn and where current knowledge is inconclusive or contradictory. Due to developments in commercial pig production, information on seasonality in pigs would be beneficial; if the pig is now photorefractory, then light regimes and hours of lighting could be excessive or under used, wasting energy or providing a suboptimal environment. Whilst the spatial acuity of pigs is poorer than humans, their ability to complete visually mediated biologically relevant tasks under different illuminances needs to be established; in addition, other parameters of lighting and their effects on pigs should also be examined.

Précis of the scientific evidence on light and pigs.

Natural biology and the evolutionary importance of light

Domestic pigs developed from wild boar species, which are most active at dawn and dusk and in shaded habitats. This suggests that the pig has a visual system that is best adapted to dim light (rather than mid-day or nocturnal light) and is also potentially adaptable to a range of illuminance. Commercial pigs are derived from a wide base of progenitor stock, including bloodlines from Asian and Northern European sources, meaning that domestic pigs may no longer be adapted to the ambient climate. The anatomy and physiology of the pig's eye also suggest generalised visual ability, with no specialisations for night time conditions or extremely bright light, but with the potential for good acuity compared with other ungulates. Pigs use vision for a wide range of tasks from foraging to communication, discriminating between individuals, and social learning: lighting should be appropriate for these tasks.

In terms of spectrum and natural lighting, ultraviolet is only likely to be relevant to pigs in terms of sunburn; pigs cannot see UV radiation and can obtain sufficient vitamin D2 from a balanced diet. When given the choice, pigs show little preference for illuminance over the range commonly used in pig units but often show a preference for familiar lighting when in a test environment. When awake, pigs prefer a lit to a dark environment but prefer to sleep in the dark.

Commercial lighting levels are unlikely to reach an illuminance that pigs find aversive - although high intensity lighting such as spotlights should be avoided - and care should be taken to avoid the presumption that pigs are suited to human-preferred illuminances. Outdoor pigs should be provided with the opportunity to avoid excessive light levels (and temperatures). Whilst pigs are visually adaptable, their tolerance to new environments should not be assumed.

There is a large body of evidence on the properties of the pig's eye and on diel activity patterns and habitat choices in wild, domestic and feral pigs; further work on these topics is unnecessary.

Spatial acuity, colour vision and flicker sensitivity

Photoreceptor and ganglion cell density within the porcine eye suggest a theoretical potential for good visual acuity compared with other mammals; about 1/6 that of humans. Experimental work shows that the pig's acuity is lower (at best 1/10 that of standard human vision). Pigs can discriminate visually between conspecifics under a range of comparatively dim illuminances. Whilst its measured acuity classifies the pig as legally blind by human standards, this conclusion overlooks other aspects of visual perception that the pig may use in daily life as well as olfaction, and audition.

Pigs possess two cone types and are considered to be red-green colour blind. Experimental evidence suggests that pigs have poorer colour perception than humans, and despite similar detection of blue wavelengths, pigs show reduced sensitivity to the red end of the spectrum. Whilst the pig's colour vision has limited impact under commercial conditions, it is an important factor when designing visual tasks for pigs or if training pigs, and should be considered when handling them, e.g. avoidance of high-contrast patterns.

Flicker perception has not been studied in the pig; according to current knowledge, temporal processing in the pig is most similar to the cat, giving flicker perception at 70-80 Hz. Further work to establish the flicker sensitivity of the pig would be beneficial in terms of the potential effects of flickering fluorescent lights.

Seasonality and productivity

The domestic pig has seasonally-influenced reproductive success, with reduced reproduction during the summer. Whilst photoperiod can play a role in reproductive development and success in both males and females, temperature is generally the predominant factor in seasonally-reduced fertility. Pigs' physiological and reproductive responses to daylength can be subtle, suggesting there may be wide variation in responsiveness of different breeds and populations. Illuminance has little proven effect on seasonality and productivity but lighting with poor colour rendering should be avoided where stockmen need to assess reproductive state. Other relevant evidence on seasonality is:

- o Piglets benefit from increasing or long daylengths (15-18 hours) (increasing suckling → improved milk composition → heavier and larger litters at weaning)
- o Long or lengthening daylengths (e.g. 16L or longer) increase food intake in grower/finishers
- o 24L (continuous light) should be avoided as it increases physiological and behavioural indicators of stress
- o Short or decreasing daylengths decrease time taken to reach puberty in males and females, and for sows to return to oestrus; these daylengths could therefore be a useful tool in breeding
- o Short or decreasing daylengths should be avoided in finisher housing (especially in mixed groups) to reduce mounting and aggression by boars and the risk of boar taint.

The wide range of findings and recommendations relating to seasonality and productivity in the pig imply that experiments were not fully controlled, maturation and developmental processes are poorly understood, there is variation in response between breeds, populations and ages, or photoperiod is not a significant factor in reproduction. Whilst some peer-reviewed literature indicates seasonal responses (as found in wild boar), commercial experience and information from farmers is often contradictory. Effects of lighting (photoperiod, illuminance and spectrum) on grower-finisher pigs are rarely reported, suggesting little effect of lighting. Temperature is more important factor than light in seasonal infertility in Britain, and genetics and housing have more effect than light on boar taint.

This contradictory evidence suggests that a large-scale fully controlled experiment – or an on-farm epidemiological study – would establish once and for all whether and by how much photoperiod affects reproduction in gilts, sows and boars under British conditions.

Welfare

Inappropriate lighting can affect welfare. Young pigs under natural spectrum lighting and under 50 lux illuminance have lower physiological measures of stress. Continuous lighting reduces welfare by increasing agnostic behaviours (indicating stress), and at bright illuminance also resulted in eye damage and weight loss; intermittent photopatterns also agitated pigs. Fighting in pigs may be reduced by introducing pigs in darkness. Most practices with severe welfare implications (i.e. continuous darkness or continuous high illuminance) are prohibited under UK legislation. Pig behaviour is affected very little by other experimental lighting factors; pigs may therefore be highly tolerant of or adaptable to artificial lighting regimes.

Pigs' tolerance to illuminance suggests that commercial lighting conditions are adequate for pigs. However, there is insufficient evidence to specify the optimum 'darkness' for productivity and welfare.

Legislation in the EU and England on lighting for farmed pigs

Photoperiod and illuminance are currently included in English legislation, and are further clarified in Defra's Code of Recommendations for pigs and in welfare assurance schemes. Spectrum of lighting is not specified nor is provision of a dawn or dusk light setting, although this is not ruled out under current legislation. Although a minimum illuminance is specified, there is little scientific evidence to back up the requirement. No maximum illuminance is specified; whilst "natural" lighting may extend into tens of thousands of lux, pigs will be able to avoid this by seeking shade or shelter. Although legislation requires that pigs are provided with a period of darkness, there is no scientific evidence for the most suitable illuminance for this, and no guidance is given on what should be provided. There are only a few regulations regarding lighting provision for pigs, which reflects not only the lack of welfare-specific research in this field (most is strictly production related), but also that lighting has only a minor role in pig welfare.

FURTHER WORK

Production and reproduction related – potential topics for further investigation

- Survey of light environments experienced by pigs on British farms, either indoors or outdoors.

- Examination of existing data sets at national level to establish the impact of seasonally-reduced fertility in commercial pigs in the UK; e.g. reproductive success of gilts, sows and boars.

- Research on:

  o illuminance and spectrum as they affect conspecific discrimination and communication, which are involved in fighting at mixing and other behaviours

  o flicker perception of pigs to ensure that fluorescent lighting is not perceived as flickering, which would have welfare consequences

  o the maximum illuminance that is perceived as a dark period (or darkness)

  o dawn and dusk periods

  o brightness perception of different commercial light sources such that recommended illuminances can be matched

  o motivation for illuminance

  o effects of different (matched-illuminance) spectra on behaviour and welfare

- Knowledge exchange and transfer on lighting for pigs, including the requirements of legislation and farm assurance schemes.

INTRODUCTION, AIMS AND OBJECTIVES

Light affects pig husbandry via one of two biological mechanisms: 1) visual perception; and 2) seasonality. Both mechanisms are strongly influenced by the ethology and evolution of the wild boar species and subspecies ancestral to the pig and their subsequent domestication. Visual perception depends on the anatomy and physiology of the eye, affecting the pig's ability to see objects e.g. pen furniture, other animals, and stockmen. Seasonal responses are mainly mediated by photosensitive bodies in the retina, affecting physiological processes such as reproduction. Both visual perception and seasonality affect the behaviour, productivity and welfare of pigs, hence lighting can have significant impact on growing and breeding pigs, kept either indoors or outdoors. Lighting for farmed pigs is subject to UK law, which is guided by EU legislation, and the welfare codes; these blend science, husbandry and farming.

Light is defined in terms of three key characteristics

      i) photoperiod – the number of hours of light per day;

      ii) illuminance/intensity - the brightness or intensity provided/perceived; and

      iii) spectrum i.e. the range and combination of light wavelengths.

Each of these on its own, and in combination with the other characteristics, affects the suitability of lighting for the pig: the pig's perception of light sources is equally important. In strict photometric terms, 'intensity' refers to the brightness of light environment, whilst 'illuminance' refers to perceived brightness, which depends on the animal's ability to detect light and its spectral sensitivity. Illuminance is an anthropocentric measurement, with the lux unit derived from standardized human spectral sensitivity and is therefore less appropriate for animal housing but is a familiar measurement. Change or range in any of the three characteristics is also influential, e.g. increasing or decreasing photoperiods provide a greater stimulus for seasonal response than constant long or short daylengths. An additional issue coincident with fluorescent lighting is the potential for animals to detect the flicker of the light source.

Given a full understanding of the various effects of light upon the sow, boar, weaner or grower, then specifications can be devised for artificial lighting to promote healthy, profitable pig production. Management of light is no different from other aspects of environmental control in pig production. Once the biological effects are quantified in terms of their effects on performance and legal requirements have been satisfied, then it is simply a matter of economics whether to manipulate light to the farmer's advantage. This argument about the degree of environmental control applies as much to pigs kept outdoors as those reared indoors.

It is appreciated that production and reproduction in the pig are the key commercial issues in this report. Scientific evidence from the literature is often conflicting; this review includes literature based on experimental research, though it is acknowledged that not all research had sufficient control of all lighting factors to draw robust conclusions.

The aim of this report is to review the biological basis of light management in modern pig farming. This will provide BPEX with the evidence needed to justify current methods of lighting management

or provide the scientific case for further investment in research (and development). The objectives of the report are:

1. To review the scientific evidence for lighting management in pig production
2. To indicate where further research on lighting for pigs is needed
3. To suggest optimal lighting environments based on current knowledge of pig welfare and production
4. To comment on the suitability of the poultry-bespoke LED for pigs and to suggest an alternative pig-tailored LED spectrum and lighting that is more suited to the pig's needs.

The review covers five key topics relating to light and lighting:

1. Natural biology and the evolutionary importance of lighting, i.e. lighting environment of the progenitor species of the domestic pig and hence their visual specialisations

2. Visual abilities of the pig; known visual parameters of the pig based on the structures of the eye and results of experiments using visual tasks

3. Seasonality and productivity; primarily effects of photoperiod on changes in reproductive success in the domestic pig, also critically reviewing evidence of different illuminances and spectra on pigs

4. Lighting and welfare; known effects of suboptimal illuminance on the pig measured physiologically, behaviourally and on changes in properties of the eye and vision, also known welfare impact on other species

5. Legislation in the EU and England; current legislation, code of recommendations and additional welfare standards in the England, basis for these recommendations and comparison with international rules.

Where possible, the report is a critical review of available peer-reviewed literature, intended to highlight known information regarding pigs and lighting and also to reveal areas where evidence is weaker, or effects of lighting parameters are unknown. The report recommends a range of areas where further research may have beneficial effects on production and welfare of pigs.

The report concludes with a separate assessment of the suitability of the tailored LED for poultry units for pig units, and a recommended spectral output curve for a similarly devised LED for the pig industry.

1. NATURAL BIOLOGY AND THE EVOLUTIONARY IMPORTANCE OF LIGHT

Domestication of the pig began 10,000 years ago, with several sites of domestication recognised across Europe and the Near East (Nowack, 1991; Oliver, Brisbin and Takahashi, 1993; Larson et al., 2005). The main progenitor species of the European domestic pig is the Eurasian Wild Boar (*Sus scrofa scrofa*), but *S.s. taivanus, S. celebensis* and *S.s. vittatus* were also domesticated (Oliver, Brisbin and Takahashi, 1993). Whilst local domesticated populations were selected for specific traits, they also reflected appropriate adaptations to the local climate, season and food availability. The "Improvement" era in the mid 18th Century saw the introduction of numerous and varied bloodlines into the European domestic pig population (Wiseman, 2000). These originated in regions where *S.s scrofa* was not the predominant progenitor species, hence incorporated traits other than those found in native wild boar, e.g. wattles for heat dissipation (Wiseman, 2000); current domestic pig breeds may therefore have sub-optimal adaptations.

The majority of progenitor boar species occupy habitats with good foliage cover, suggesting that their vision may be suited to subdued natural light (only *S.celebensis* is noted as mainly diurnal; Oliver, 1995). Most wild boar species and feral populations of pigs show crepuscular behaviour (Blasetti et al., 1988, Boitani et al., 1994, Jensen 2002), although human activity such as hunting, high or low temperatures and changes in food availability can induce nocturnal or diurnal behaviour patterns. Domestic pigs similarly show a more crepuscular activity pattern (Simonsen, 1990) than a conventionally diurnal one. This crepuscular origin likely equips the pig with a visual system that is able to cope adequately with a comparatively wide range of intensities (e.g. very dim to relatively bright light), and may also make its visual system more adaptable than a species specialised to nocturnal or diurnal activity.

Wild boar and domestic pigs demonstrate use of vision in a wide range of biologically relevant settings, e.g. communication with conspecifics, reaction to aversive stimuli, and preference for different illuminances.

1.1 Visual behaviours

Pigs are highly social, hierarchical animals and therefore require some form of communication and individual or group recognition, both to keep the group together and also to maintain the hierarchy without repeated fighting (Ewbank and Meese, 1974). Olfactory and audible cues are normally used but some communication also incorporates visual cues e.g. raising a crest in confrontational situations in wild boar (Darwin, 1872). Jensen (2002) notes that a much wider range of signals is used, involving general posture and specific positions of the tail, ears or head. Aggressive animals may perform a parallel walking display, which likely includes some form of visual assessment (Erhard and Mendl, 1997). Males of various wild pig species have visible structures, such as hair tufts on the ear, cheek or snout, wart-like skin outgrowths, and contrasting patterns of hair and hair colours (Frädrich, 1974), that are likely to contribute to communication, through association with reproductive fitness or fighting. Mcleman et al., 2006 and O'Conner et al., 2010 (in press) showed that pigs can discriminate between conspecifics using vision alone. Many of these visual structures are not observed in the domestic pig (Watson, 2004); reduced signalling potential for communication may also have reduced pigs' ability to communicate visually with one another, potentially contributing to the high level of fighting seen when strangers are mixed. Pigs therefore need an appropriate light intensity to see and correctly interpret visual information provided by conspecifics.

Wild boar show vigilance behaviour, especially when feeding as a group with young (Quenette and Gerard, 1992; Quenette and Desportes, 1992). Wolves hunting wild boar approach from downwind (Kerwood, 2005), so the boar's well-developed olfaction is unable to detect their advance, therefore relying on vision to detect predators. In commercial farming, visual detection of predators is less vital; however, pigs may perform vigilance behaviour, so denying them the ability to see possible threats at a distance could potentially compromise their welfare and induce stress.

Social learning also indicates use of vision; pigs can learn the position of food, colour of food trough and a degree of paddle pressing from observation of siblings (Nicol and Pope, 1994). They wait until out of the line-of-sight of a more dominant individual when locating a known food source in order to avoid competition (Held et al., 2001). Broom, Sena and Moynihan (2009) showed that pigs can learn the location of a food source using mirrors. Done, Wheatley and Mendl (1996) showed that pigs prefer to feed from larger food containers, even if less food is present, suggesting that foraging behaviour is influenced by vision; and a range of operant experiments have shown that pigs can learn to associate a visual cue with a food reward (Klopfer, 1966; Tanaka et al., 1998; Croney et al., 2003; Taylor, 2006). Thus, vision has some role in foraging, even if light *per se* is not vital for feeding itself (pigs gain weight even in 24 h darkness (Ntunde, Hacker and King, 1979)), so sufficient light should be provided to enable pigs to use their vision in this way.

1.1.1 Use of colour vision by the pig

Vision is used to some extent during foraging and pigs show the ability to recognise and associate a colour with a food source (Nicol and Pope, 1994; Croney et al., 2003). Experiments with dyed grains showed that the pigs preferred blue over green and black food (Kleba, Hone and Robards, 1985). Avoidance of this same colouring at higher concentrations suggests that the original preference was probably based on colour rather than flavour of the dye. Hutson et al., (1993) suggest that sows were neophobic to blue food. Both experiments suggest that pigs can perceive blue wavelengths as somehow different to the other dark colours used, assuming scent of the dye was not an issue. Pigs showed a consistent startle response to the warning colours of black and yellow, although this could reflect detection of the high contrast pattern, rather than just colours (Hutson et al., 1993).

Jankevicius and Widowski (2003) compared the attraction between artificial 'tails' soaked in blood, saline or dye to investigate pigs' preference for factors of bitten tails. The colour of the tails, created by different concentrations of the same dye, had no effect on the attractiveness of the cue to the pig, thus unlike chickens (Barbur et al, 2002), pigs do not appear to be attracted to wounds on other animals by the visual appearance of blood.

Eurasian wild boar are not renowned for the striking colouration or ornate patterns of their pelage; it is unlikely that colour displays play a strong role in communication in their social groups. However, visible markings in wild pig species are mainly striking shapes or sizes, and contrast visually with the background pelt colour suggesting that contrast, size and shape discrimination may be of more importance to pigs. Although domesticated piglets have clearly different colourations, this is likely to provide camouflage against predators (Oliver, 1993).

1.2 Ultraviolet

Whilst photoperiod, intensity and spectrum of natural light are rarely recreated in indoor situations, individual characteristics e.g. photoperiod, are often studied separately, as shown in Section 4, although daily variation in these factors is rarely studied. Presence of ultra-violet wavelengths in natural light has additional implications for rearing pigs.

Poultry can detect ultra-violet (UV) wavelengths (which are beyond human perception), and show preference for artificial lighting environments with supplemental UV (Moinard and Sherwin, 1999), while hens select cocks lit by additional UV (Jones et al., 2001). There is no evidence for UV markings on pigs, making UV presence unnecessary for communication, and pigs are highly unlikely to detect UV (Taylor, 2006; Klopfer 1966), suggesting that UV reflectance of foodstuffs is not relevant. UV is necessary for synthesis of vitamin D3 in humans and pigs; Cooper et al., (1997) extrapolated that 1-2 minutes exposure to natural UV levels per day is sufficient for pigs to produce adequate levels of the vitamin; however, standard pig diets contain vitamin D2, and there appears to be no additional need for D3. Exposure to UV radiation places pigs at risk of sun burn; hence the need for additional shelter and mud wallows for outdoor animals; indoor animals should similarly be able to avoid direct sunlight (window glass excludes UV light). Correct vitamin D provision is important in pig production: Lauridson et al., (2010) found a decrease in the number of stillborn piglets when using 1400 IU vitamin D or higher. Gilts showed improved bone strength and bone ash content when more than 800 IU vitamin D3 were provided. Bethke et al., (1946) showed that vitamins D2 and D3 are equally effective in supplying the vitamin D needs of swine.

1.3 The porcine eye: implications for vision

The physical properties and structures of the eye can provide evidence for the visual abilities and limitations of a species and hence to which light environments it may be best adapted. The human eye is physically similar to the pig's eye in gross structure, making it a useful comparator (e.g. Curcio et al., 1990; Olsen et al., 2002; Gloesman et al., 2003), and allowing subjective comparison of the effects that quantitative differences may have on the perceived image. The porcine eye combines characteristics of both herbivores and carnivores:

- Pupil size range 5mm-11mm (Dureau et al., 1996, Zhao et al., 2000) – similar to humans, suggesting suitability to similar intensity range, possibly less suited to vision in high light intensities (minimum pupil size in humans 2-3 mm) (Land and Nilsson, 2002)
- F number (index of light gathering ability) 2.4-1.97 in low light, 4.33 in photopic (bright daylight) conditions (Taylor, 2006) giving pigs very similar light gathering abilities to the human eye in nocturnal conditions, but suggesting mesopic (intermediate illuminance level) visual adaptation
- Pupil shape – round (unlike most ungulates)(Land and Nilsson, 2002) – implies that the pigs' eye is not adapted to bright sunlight (circular pupils cannot contract as tightly as slit or oval pupils); however the pig could behaviourally avoid this environment
- Corpora nigra – none present, its presence indicates adaptation to bright light environment where the retina needs additional shading
- Iris colour – blue to dark brown in domestic animals (Grandin and Deesing, 1999), yellow to dark brown in wild boar – variation suggests little evolutionary pressure on eye colour - darker

- irides allow less light through to the retina than pale irides (Shear, O'Steen and Anderson, 1973)
- Refractive index of +1.3D (±2.3D) and corneal power of 44.1D (± 1.5D) - minipig eyes are still similar enough to use for human comparisons (Nielsen and Lind, 2005)
- Lens:eye diameter of 0.44 (Taylor, 2006) - suggests dawn and dusk (ahemeral) activity pattern rather than diurnal or nocturnal
- Limited to non-existent accommodation (Wesley and Klopfer, 1960; Duke-Elder, 1970; McMenamin and Steptoe, 1991; Gelatt, 1998; Vilupuru and Glasser;, 2001; Neilsen and Lind 2005) reduced or inability to focus on near objects
- Tapetum - absent. Its presence would suggest nocturnal adaption, however, nocturnal animals such as the rabbit and owl monkey also lack tapeta (Kirk, 2004)
- Retina – high receptor density compared with other mammals (83,000 to 2000 cells/mm^2 (Chandler et al., 1999); ratio of rods to cones 8:1 – (Gerke, Hao and Wong, 1995, Chandler et al., 1999) potential for colour vision and comparatively high acuity
- Ganglion cell density – high ganglion cell density (>1,000 cells per mm^2, peak of >5,000 cells/ mm^2) (Hebel, 1976) – suggests good transmission of information from retina

Lower photoreceptor and ganglion cell density in the domestic pig than wild boar (Ahnelt, 2002) and smaller visual cortex (Kruska and Stephan, 1973), suggest that domestication has reduced the necessity to detect and process visual information (or that factors associated with vision have not been selected).

Domestic pigs appear to have no visual specialisations towards strictly nocturnal or diurnal activity patterns, but more mesopic (intermediate) light. This relates to natural light intensities, rather than artificial lighting which will almost always be less bright than natural photopic illuminance. Natural illuminance ranges from 0.01-0.1 lux (night) up to 40,000 lux (bright, mid day), with peak visual ability in the human at 16,600 lux (Varkevisser et al., 2002). Common illuminances recommended in farm environments for human vision are 200 lux for dairy milking, and 1000 lux for bench and machine work (Kaufmann, 1966). Although vision is not the pig's primary sense, in an atmosphere where olfactory and auditory pollution may be high, pigs may become more reliant on vision.

In summary, the various structures of the porcine eye give some indication of the conditions under which porcine vision originally evolved; however, reliance on vision may be less important to the pig than olfaction and audition (Frädrich, 1974) and reduction in both brain structures and in ganglion and photoreceptor cell density in domestic pigs in comparison with wild boar / wild hogs suggest that a lower use of vision, olfaction and audition than their progenitor species. Anatomical evidence provides useful information on the likely light environments to which the pig is adapted. However, the presence of specific adaptations does not mean that the animal necessarily employs them (Pettigrew et al., 1998).

1.4 Light preferences

Experiments under controlled conditions, where effects of light can be separated from other environmental factors such as temperature, have been carried out on a range of pig populations. These experiments show the preferences of pigs for illuminance and darkness.

1.4.1 Preference experiments

The most basic preference is between light and darkness; Hacker, Bearss and Forshaw (1973) found that when growing pigs were given a continuous choice between an illuminated and a dark compartment, they spent most time in the dark (75%), but showed no clear circadian rhythm of preference, with short bouts in each compartment (1.83 h in dark v 0.82 h in light) and an average of over 10 transitions between the compartments per 24 hours. Observations of the pigs showed that the pigs preferred eating in the lit compartment; illuminance and source were not specified.

Juvenile pigs (7 weeks and 11 weeks old) given a choice between <4, 4, 40 and 400 lux showed a clear preference to spend time in the <4 lux compartment, mainly due to sleeping/resting behaviour, with similar proportions of their active time, including eating and drinking spent in all illuminances (Taylor et al., 2006). Whether pigs chose to enter the dimmest compartment in order to sleep, or whether sleep was induced by entering the dimmest environment cannot be resolved from this work.

Tanida et al., (1996) investigated the behavioural responses of piglets to darkness and shadows. One-week old piglets were isolated in a test box, and their response to access to an adjacent test box with a different light environment was measured. All combinations of access to dark and light were used, additionally going from dark to dark + dazzling light beam, and into dark with a light beam from behind the piglet. The lighting used to create the bright environments was 2,100 lux at piglet eye level, compared with dark at 5 lux, or the beams at 160 lux. The authors concluded that piglets significantly feared staying in darkness, tending to move towards brightly lit areas (in contrast to deer held in isolation (Pollard and Littlejohn, 1995)), and were also frightened by spotlights and the painted black and white patterns. The use of dazzling and backlit light beams aimed to study Grandin's assertion that pigs do not choose to walk into a dazzling light source (Grandin, 1988); however this dislike was not found with these piglets (in this case though the beam was only 160 lux, the piglets were also not averse to entering a 2100 lux compartment). The avoidance of the black and white patterns could indicate problems with depth perception (Grandin, 1988), or reaction to striking patterns of contrast (such as warning colouring) (Hutson et al., 2000) rather than illuminance preference.

1.4.2 Preference and familiarity

Pigs and piglets are often shown to prefer a lighting environment similar to their home pen in choice situations; whilst it is possible that the animals' eyesight adapts to its home pen lighting, it is more likely to be due to the animals' familiarity with that environment, and preference to return "home" from a novel or isolated environment. Christison et al., (2000) showed that piglets offered a choice of creep illuminances were more likely to select their home pen lighting, and that light itself was neither strongly attractive nor aversive. The experiment specifically used piglets from different rearing illuminances to allow this potential bias to be factored into the analysis. It is therefore possible that piglets in the work by Tanida et al., (1996) may have been selecting their home pen illuminance (lit with artificial and natural light), i.e. a "bright" environment; this behaviour may have been unintentionally encouraged by previous use of nursing grunt recordings to encourage the pigs to enter the alternate compartment.

The work by Taylor et al., (2006) aimed to reduce effects of pigs' association of temperature, familiarity, lying area, and food and water access with illuminance by rearing the pigs under a light gradient which changed direction every two days and where feeders were moved between pen locations and illuminances. However, the experiment imposed a minimal cost for choosing illuminances, pigs could walk freely between illuminances and the physical distance between different illuminances was small; providing the pigs with much larger enclosures would be more realistic to commercial conditions and could help tease out underlying preferences by increasing the cost of choosing a suboptimal environment.

Phillips, Thompson and Fraser (1988) investigated whether illuminance affected pigs' preferred environment for walking up ramps. Whilst no significant effect was found, the authors noted that the illuminance closest to the pigs' home pen environment (80 lux) was preferred.

Preference tests can only be interpreted accurately when the options available cover a suitable range of environments, and where options for which there is no natural correlate are avoided. The animal may also only be able to select an environment for its short-term occupation; if it was aware it would be confined in its selected environment for an hour, it may learn to select differently from occupancy durations of five minutes or a week. Pigs can show a degree of time appreciation (Spinka, Duncan and Widowski, 1998); preference experiments could therefore be combined with prior training on length of confinement to give a more detailed picture of pigs' preference for different periods of light.

The range of welfare indicators described in Section 4 can be used to confirm the wisdom of pigs' selections in preference experiments, either during or after occupation of the controlled environment. Additionally, observations of the animals' behaviour patterns during their occupation of a preference chamber can indicate their tolerance for non-preferred environments for different behaviours.

1.4.3   Motivation experiments

Motivational measurements provide an idea of how important that environment (or facility) is to the animal, which is more likely to reflect a behavioural or physiological need rather than just preference. Whilst preference is generally measured as time spent in each environment, or as number of times of entry to each compartment each time the subjects are removed, the animal's distribution of its time may change if the resource is given a cost (Cooper and Mason, 2000). Five minutes per day of access to 100 lux may be as important to a species as nine hours of darkness, but this cannot be determined in free-choice experiments. Many experimental factors may affect the preference measured, e.g. stocking density, age, sex, duration of occupancy etc of the animals.

A series of motivation studies by Baldwin and Meese (1977) showed that when pigs were able to switch lights on for brief periods (up to 20 seconds per activation), the light (350 lux) was kept on for less than 1% of the time, indicating that motivation was weak and/or the animals preferred to be doing activities other than controlling light onset. When the animals could switch their pen lights both on and off, the lights were kept on for approximately 72% with some proportion of each hour unlit but no long periods without light. Baldwin and Meese concluded that pigs showed a strong preference for light over darkness despite light onset itself being only weakly reinforcing.

These results may again demonstrate pigs' preference for home pen lighting, additionally the onset of 350 lux in an otherwise dark environment may have been aversive due to the initial glare;

explaining why motivation to turn the light on was weak, even though a lit environment was actually preferred. The effect of anosmia on this preference was also examined, but there was no significant effect on the amount of light obtained – reduction in olfaction did not increase pigs' reliance on visual information.

Summary - Natural biology and the evolutionary importance of light

Domestic pigs have been developed from wild boar species, which are predominantly crepuscular or active in shaded habitats, but are able to adapt their behaviour patterns according to temperature, predation and food availability. Pigs are derived from a wide base of progenitor stock, meaning that domestic pigs may no longer be adapted to their current physical environment. Pigs use vision for a wide range of tasks from foraging to communication and social learning: lighting should therefore be appropriate for this. Ultraviolet is only likely to be relevant to pigs in terms of sunburn; pigs cannot see into UV and can obtain sufficient vitamin D2 from a balanced diet. Structures of the pig's eye suggest generalised visual ability, with no specialisations for scotopic conditions or extremely bright light, but with the potential for good acuity compared with other ungulates. In preference and motivation experiments, pigs show little preference for different intensities; in general some light is preferred to darkness, pigs prefer to sleep in the dark, and often show a preference for familiar lighting environment when in a test situation.

Implications
Commercial lighting is unlikely to reach intensities that pigs find aversive, but it should not be presumed that pigs are suited to human-preferred intensities. Outdoor pigs should be provided with the opportunity to avoid excessive light intensities (and temperatures). Whilst pigs are highly adaptable, their tolerance to new light environments should not necessarily be assumed.

Further work
The actual preference and motivation for different intensities (rather than darkness v light) is still unknown for the pig; a series of experiments to investigate this would provide useful information which could have benefits for pig production. Similarly, different commercial spectra/ light sources should be examined. Different ages of animal should be used (e.g. farrowing sows may have different priorities) and care should be taken to reduce bias in pigs' selection. This research is of low priority – pigs have shown adaptability to a wide range of light environments, hence it may have limited impact on productivity when other environmental features are well controlled, but may be an additional factor towards a more optimal environment when other factors are less than ideal, increasing pigs' tolerance to their environment. Finding out the effects of lighting on a range of relevant visual tasks e.g. conspecific recognition and fighting would have additional welfare and production benefits.

2. SPATIAL ACUITY, COLOUR VISION AND FLICKER SENSITIVITY

2.1 Spatial acuity

Acuity is the upper limiting point of spatial vision it gives information on the perception of fine detail, but nothing on the perception of shapes or forms in the real visual environment. Acuity is a useful measure of the visual ability of the eye or animal to distinguish between visual cues which could therefore play an important role in its daily behaviour. An animal may need good visual acuity for a number of reasons, such as familiarity and ease of movement around its environment (Phillips et al., 2000), discrimination or recognition of other animals (D'Eath and Stone, 1999) or stockpeople (Zulkilfi et al., 2002), and locating food and water (Davis et al., 1999; Prescott and Wathes, 2002). Good visual acuity could help to reduce fear in livestock by enabling them to discriminate or recognise objects in their environment (Zulkilfi et al., 2002). Alternately, good acuity may increase fear of humans or other objects of which the animals were previously unaware (Fall, 1974), or could increase the visibility of objects to manipulate in stereotypical behaviour (Van Putten, 1980) if other factors of the environment are unsuitable. A better measure of spatial vision (which incorporates acuity and addresses the perception of more complex visual patterns) is the spatial contrast sensitivity function (CSF) (Jarvis and Wathes, 2008). Nevertheless, acuity is relatively straightforward to measure compared with the CSF and represents an important and accepted metric. It gives a useful indication of relative spatial vision when different species are compared.

Two approaches are used to estimate visual acuity; indirect calculations based on structures within the eye (i.e. eye size, photoreceptor and ganglion cell density) and direct measurements. Calculations based on physical structures can estimate the maximum potential acuity of the pig but do not say anything about interpretation of this information by the live animal. Conversely, operant conditioning techniques may be restricted by the ability of the animals to learn the visual task, or limitations of the apparatus or experimental procedures.

2.1.1   Units used to quantify acuity

The angle subtended by the relevant feature of the visual stimulus is described in degrees (°), minutes (') and seconds ("), where 60" = 1' and 60' = 1° (Norton, Corliss and Bailey, 2002). Describing a stimulus in terms of the visual angle subtended allows data to be compared more easily, and avoids the need for constant repetition of the stimulus size and viewing distance. In some instances, acuity is given as a unitless value of 1/(viewing angle in minutes of arc) (e.g. Tanaka et al., 1998); in these units, poorer acuity is represented by a larger value.

2.1.2   Ganglion cells and acuity

The pig's eye has a potential resolving power of 3.46 minutes of arc based on eye parameters and ganglion cell density (calculations in Taylor, 2006), well below the human's acuity of 60 minutes of arc, and similar to the marmoset, cat (Pettigrew et al., 1998) and elephant (Stone and Halasz 1989). Table 1 in the Appendix shows other species for which published values have been calculated in this way or using similar anatomical calculations. It should be noted that ganglion cell density gives the best possible acuity, but ignores loss of information caused by the optical components of the eye (Jarvis and Wathes, 2007)

Ideally all acuity experiments should include 1) the illuminance and spectrum provided during the experiment, 2) the distance at which the animal's acuity is measured, and 3) the number and age of animals involved, in order to enable inter-species or inter-individual comparisons.

2.1.3   Spatial acuity in the pig

Zonderland et al., (2008), found that pigs' acuity varied very little over an illuminance range from 0.5 to 80 lux (pigs otherwise housed in 250 lux). At all illuminances gap sizes of 10 and 20mm were infrequently distinguished by the pigs, whereas differentiation of 30 and 40mm gaps was more accurate. However, acuity was low at 0.03 to 0.001. Pigs were expected to visually select their target at a maximum of 1m, but some pigs still failed to distinguish the 40mm gaps correctly in the at distances of less than 200mm. Using similar visual cues, Tanaka found that pigs' acuity was 0.07 to 0.017 under 550 lux and presented at 1.8m, but work by Taylor (2006) found that pigs were unable to distinguish Landolt Cs even when an acuity of 0.66 was needed (gap presented a 1.79° visual angle, viewing distance 1.6m). (The test illuminance in Taylor's work was variable 36-229 lux, experimental set up incomplete). Longer viewing distances and higher illuminances could potentially contribute to higher acuity measurements in the pig; short viewing distances may be suboptimal as the pigs' eye has limited to no accommodation. Spatial acuity of a range of animals has been determined behaviourally (see Table 2 in Appendix).

In human terms, an acuity measurement of 0.1 is termed "legally blind", and 0.04 is classed as "profound visual impairment" (see Table 3 in the Appendix), pigs therefore have very poor acuity by comparison with humans. This conclusion corresponds with the ganglion cell calculations of Pettigrew et al., which predicted that pigs would have a maximum acuity approximately 1/6 that of humans, i.e. 0.16 (or porcine resolution of 1 mm at 1 m compared with 0.16 mm in humans).

Biologically relevant stimuli will contain a wide range of cues other than those reliant on acuity, e.g. shape, movement, and colour. Visual ability (NB not acuity) in the pig may therefore be better illustrated using visual conspecific recognition at set illuminances and distances, as demonstrated by Mcleman et al., 2008 and O'Connor et al., 2010 (in press). Pigs can visually distinguish related but unfamiliar conspecifics at a viewing distance of 1 m under a range of illuminances (70 lux, Mcleman et al., 2008; 40 and 200 lux, O'Connor et al., 2010 (in press)), which strongly suggests that their perception of features in the real world will be influenced by factors other than basic acuity

Pigs can distinguish between visual cues based on overall size of the cue, allowing the Weber fraction to be determined. The Weber fraction is the smallest difference between two stimuli that is detected, expressed as the difference between the two cues divided by the largest cue. In humans, the Weber fraction for line length is quoted as 0.029 or 2.9% (Coren, Porac and Ward, 1978), so a 9.7 cm line is distinguishable from a 10 cm line and 97 cm line is visibly different from a 100 cm line. Weber fractions for the pig based on cue area discrimination (Landolt rings) by the pig (four gilts only) gave fractions from 0.3 to 0.64 (Taylor, 2006), similar to values for adult dairy bulls of 0.5 to 0.75 (Rehkämper and Görlach, 1997). Weber fractions can provide useful information on pigs' visual ability to discriminate between objects in their environment, which potentially affects discrimination between pigs, or stockmen; object size discrimination has been shown to have a role in foraging behaviour (Done, Wheatley and Mendl, 1996), and size discrimination of individuals plays in important in fighting and dominance hierarchy (Rushen, 1987).

2.1.4   Spatial acuity - Summary

The acuity calculations for the pig suggest it has the potential for good acuity for an ungulate, but with, at best, a sixth of the resolution of the human; behaviourally derived acuity is even lower. Pigs may be more attuned to detect or discriminate other features of visual stimuli rather than spatial detail, e.g. movement, shape, edge detection etc. Whilst the pig's acuity may be inferior to humans', their visual gearing towards additional components of visual information should not be underrated, and the importance of appropriate lighting for visual tasks should not be underestimated.

2.2 Spectral sensitivity

Spectral sensitivity is the ability to discriminate different wavelengths of light, i.e. to see in colour. To have colour vision, an animal needs to have at least two types of photoreceptor cells, and be able to simultaneously process information from both types (Schnapf, Kraft and Baylor, 1987). The perception of different wavelengths depends on the combined sensitivity of the cone types and the neural transfer of information. Different species differ in their detection of different wavelengths; in terms of the range of visible wavelengths, the degree of sensitivity to colour information, and the different sensitivity to wavelengths within their visible range. Despite the assertion in Home Office codes of practice that "few laboratory animals apart from primates (and perhaps cats) have colour vision" (Home Office, 1996), its existence has been proved in many avian and mammalian orders, including many farm and laboratory species.

2.2.1   The visible spectrum

The visible spectrum is a small region of the electromagnetic spectrum from about 360-720 nm that is detected by the human eye. The terms "infra red" and "ultraviolet" refer to the wavelengths just outwith the range visible to humans, and the ability of other species to detect these is often overlooked. The perception of named colours is subjective (and there can be large differences between individuals who have normal colour vision). Even when individuals use the same colours to refer to the same specific wavelengths, how the brain perceives these colours cannot be determined.

2.2.2   Cone types and distribution

Most mammalian orders have two cone types, one with peak sensitivity in the short wavelength region (blue), and another in the medium to long-range region (green – yellow - red). This allows comparison of the short wavelength component against medium to long wavelengths, giving colour vision, but most species will be red-green "colour blind", being unable to distinguish red wavelengths from green ones. In contrast, humans and some other primates have three types, enabling additional contrasts in the medium to long range contrast (i.e. green v red differentiation). Mammalian retinae generally contain low numbers of S cones (short wavelength receptive) and higher numbers of M (medium wavelength) or L (Long wavelength) cones (Peichl and Moutairou, 1997; Hemmi and Grünert, 1999).

In the pig, both S and M cone types are found throughout the retina, and almost all regions have mean S cone percentage >10% (Hendrickson and Hicks, 2002). The S cone density is significantly higher than that in humans, which potentially enables the pig to be more sensitive to blue wavelengths than the human, and over a larger area of the retina. The distribution of the rods and cones in the porcine retina suggests adaptations for best acuity in the horizontal panorama from the eye, with good levels maintained for observing objects from eye-level down to the ground, but

relatively uniform distribution of cone types within this area suggesting that there is no specific spectrally sensitive area, with the whole retina equally capable of detecting colour information.

2.2.3   Measuring spectral sensitivity

As with acuity, spectral sensitivity can be estimated from the anatomy of the eye or by behaviour; indirect methods such as electrophysiology show the abilities of the cone types, but not the perception by the animal. Electrophysiological studies of the cone cells of pigs show two classes of receptor with peak sensitivities to 439 nm (blue) and 556 nm (green) wavelengths (Neitz and Jacobs, 1989). The short wavelength cone of the pig is most similar to the sheep, goat and tree shrew and possibly cat (depending on source); the medium/long cone is most similar to the cow, sheep, cat, dog and tree shrew (see Table 4 in Appendix). The main pressures on the specificity of the cone types are phylogeny and subsequent ecological adaptations.

Behavioural and electrophysiological data are highly correlated, showing the validity of both methods in determining complementary aspects of spectral sensitivity (Tovee, Bowmaker and Mollon, 1992), the two methods supplement each other to produce the fullest picture of colour vision in an animal.

2.2.4   Behavioural methods – self coloured cues

Initial attempts to show colour vision in animals including the pig were based on training animals to discriminate coloured cues e.g. cards. A range of methods have been used e.g. discrimination between two colours or one colour v grey cues (Eguchi et al., 1997). The major problem is that the animal may be able to distinguish the stimuli using other cues, especially brightness, UV dyes, scents of dyes etc. Attempts to match the brightness of different coloured cues are automatically limited by using human vision or anthropocentric devices to match brightness, which is inherently different from spectral sensitivity of the animal being tested (Barber et al.,2006, Taylor, 2006; Prescott and Wathes, 1999; Saunders, Jarvis and Wathes 2008). An alternative method is to measure the animal's discriminative abilities over a range of cue brightnesses, e.g. using a variety of light and dark greys per set of cues (horses - Smith and Goldman, 1999) or by using dark colour versus light grey and light colour versus dark grey stimuli (fallow deer - Birgersson, Alm and Forkman (2001)). These techniques give a more useful set of discriminations, but are limited by the number of animals, trials and repeated task learning involved.

Despite this limitation, self-coloured cue discrimination has provided potentially valuable information on colour perception in pigs. Where the animal successfully distinguished between cards, some visual property such as wavelength or brightness (or both) enables discrimination, suggesting its sensitivity to some wavelengths is different to human perception.

The consistent results of coloured cue discrimination by pigs (e.g. Eguchi et al., 1997 *S.s. leucomystax* and Tanida et al., 1991) are that pigs' perception of blue cues is different from their perception of grey, green or red cues, and they struggle to discriminate between the latter three cues. Pigs may have found the blue cue identifiable on brightness alone; they may have different spectral sensitivity to humans - making blue identifiable due to brightness of the wavelength, or they may be able to distinguish between the blue and other cues based on wavelength. Their difficulty in distinguishing between red, green and grey suggests either that brightness discrimination was not possible because

human and porcine sensitivity to these colours is similar, or that the pig cannot distinguish red from green based on wavelength.

2.2.5   Illuminated cues

The spectral sensitivity of the animal can be investigated using brightness perception, typically using illuminated coloured cues. The animal is presented with lit and unlit stimuli and trained to distinguish between them using brightness alone, with brightness of the lit source varied incrementally until a threshold of perception is reached. This method has been used successfully in the domestic chicken (Prescott and Wathes, 1999), turkey and duck (Barber, 2003), and pig (Taylor,2006).

Klopfer (1966) showed that pigs could detect wavelengths between 420 and 760 nm when these were presented separately, but could not detect 820 nm at the intensity provided. Individual pigs were then trained to identify a panel lit by a specific wavelength (680, 575 or 465 nm) in order to receive a food reward, and had to discriminate between that and other wavelengths presented. The pigs showed different levels of sensitivity to the wavelengths presented, with a peak in sensitivity at 550-595 nm, and a smaller peak at 465 nm. These results were based on minipigs (Pitman-Moore and Palouse) and the results show differences in spectral sensitivity between breeds; thus differences between these two breeds and commercial strains could be much larger.

Incremental spectral sensitivity work by Taylor (2006) identified pigs' sensitivity to each of a range of 13 specific narrow band wavelengths. Pigs could detect wavelengths from 380 to 694nm, with a peak in most pigs to "blue", either to the 415 nm or 450 nm with reduced sensitivity below 380 nm ("far blue") and red (above 577 nm) ends of the spectrum; human data (on the same equipment and with the same lighting) showed a peak at 450 nm. Pigs showed similar sensitivity to blue wavelengths, but reduced sensitivity to red wavelengths compared with humans – all humans (8/8) could detect 694 nm, but only 3/6 pigs could detect this and needed higher intensities.

2.2.6   Colour Vision - Summary

Colour vision in pigs is similar to most ungulates and ruminants, with two cone types present. Pigs have dichromatic vision with a similar but reduced sensitivity compared with humans.

2.3 Flicker sensitivity

An additional characteristic of artificial lighting, which may influence its appropriateness for use with animals, is the 100 or 120 Hz flicker inherent in magnetic ballast fluorescent sources (Kaufmann, 1966). Less study has been done on this aspect of lighting, especially with regard to mammals, although it has been studied in poultry (Jarvis et al., 2002) and starlings (Greenwood et al., 2004). Under visible frequencies of flicker, humans report a variety of unpleasant effects that increase with the visibility of the flicker, e.g. visual fatigue (Brundrett, 1974) epileptic fits (Trenite, 1998), headaches and migraine (Wilkins et al., 1991).

Based on the Rovamo model (Rovamo, 1999) and its application (Jarvis et al., 2003), the current best estimate for critical fusion frequency (CFF), in the pig is 70-80 Hz, based on a similar α wave response time to the cat (Rosolen et al., 2005; Rosolen et al., 2008); Dodt and Enroth found a CFF in the cat of 70-80 Hz, strongly suggesting that the pig will not see flicker from correctly functioning fluorescent

lighting, however differences in processing speed of mechanisms subsequent to the retina in the two species could affect this assumption.

Pigs may be able to detect the 50 or 60 Hz flicker of fluorescent light sources as they begin to fail, so light sources which flicker visibly to humans should be removed from pig housing. This effect may also be relevant when light enters the pigs' environment through a rotating fan.

Summary – Spatial acuity, colour vision and flicker sensitivity

The anatomy of the porcine eye suggest the potential for good acuity in the pig compared with other mammals but only about 1/6 that of humans. Experimental work gives acuity of lower than this (at best 1/10 that of standard human vision). Spatial contrast sensitivity function in the pig is still unknown and give more useful evidence on pigs' perception of their environment. Pigs possess two cone types and can therefore be assumed to be red-green colour blind. Spectral sensitivity data suggest that pigs have poorer colour perception than humans. Flicker perception has not been studied in the pig; according to current knowledge, temporal processing in the pig is most similar to the cat, enabling flicker perception at up to 70-80 Hz.

Implications
Measured acuity in the pig classifies it as legally blind by human standards, but this overlooks other key facets of visual perception that the pig may use in daily life. It also emphasises the key roles that olfaction, audition and touch have in the pig's perceptual world; this should not be overlooked when pigs move to novel environments. Whilst the pig's colour vision has limited impact in commercial conditions, it is an important factor when designing visual tasks for pigs or if training pigs. Pigs are unable to perceive the flicker of normally functioning fluorescent lights.

Further work
Effects of illuminance and spectrum on conspecific discrimination need further investigation, and establishing the spatial contrast sensitivity function would give a better indication of the visual world of the pig, and hence factors to be aware of in pig housing, moving and handling. The critical fusion frequency of pigs should be established experimentally to ensure that when pigs are housed under fluorescent lighting they do not perceive flicker, which would have welfare consequences. Work could be done to establish brightness perception of different commercial light sources such that recommended intensities can be matched. Pigs' inability to detect human-visible red wavelengths could be explored e.g. can pigs be calmed by housing under red light (e.g. at lairage, or in farrowing housing)?

3 . SEASONALITY AND PRODUCTION

Light has both direct and indirect effects on productivity, e.g. weight gain, food uptake and feed conversion rate; pigs also show seasonal fluctuation in reproduction (rather than strict seasonality). Different degrees of seasonality are reported from different countries, ranging from distinct short day breeders (Love, Evans, Klupiec, 1993), conventionally in countries from 50-60° North and 30-40° South (Hoste and Oakenfull, 1999) to no seasonal changes (Okere, 2001). The variation in seasonality may reflect the origins of the domestic pig, with input from progenitor species whose seasonality would be determined by the climate in which they evolved, as well as the current climate experienced by farmed animals. As with poultry (Morris, Sharp and Butler, 1995), commercial pressures will have encouraged selection for photorefractoriness in pigs in order to reduce fluctuation in productivity. Most commercial pigs are no longer strictly seasonal, i.e. most breeds are expected to have more than two litters per year, so photoperiodism should not be readily apparent.

European wild boar maintain a more obvious seasonality, with a rut in October/November, gestation from December with peak farrowing in March-April and an anoestrous period in the sow from June-July through till late autumn in mature animals. The pattern in primiparous sows is subtly different, with gestation through April-July and piglets born in July-August (Vassant 1995). This is thought to be because gilts (born March-April) need over a year to mature. Experiments frequently use gilts to compare light treatments because gilts are known to be more seasonally responsive than sows; however, if domestic pigs are still governed by this difference in breeding period due to age, whilst sows would be expected to adhere to short day breeding pattern, gilts may similarly come into oestrus under decreasing daylengths if mature enough to breed, or may show delayed puberty, with oestrus triggered by increasing daylengths to coincide with the next "spring".

The most obvious remaining influence of season on reproduction in the pig is a period of reduced fertility or anoestrus during the summer; in the wild boar, full anoestrus is recorded, however in domestic breeds this often shows as a reduction in piglet numbers and slow return to oestrus. Whilst light plays a role in seasonal responses, high temperatures undoubtedly reduce boar, sow and gilt fertility (Skinner et al., 1999, McGlone et al., 1987, Love 1978, Cameron and Blackshaw, 1980).

Seasonality is controlled by melatonin in response to photoperiod (Skinner et al., 1999). Melatonin is the regulatory hormone synthesised when light is not detected by the retina (Menaker, 2003); although it is detected by photoreceptors, the melatonin system is independent of the visual system. Melatonin is associated with stimulating sleep and regulating daily biological rhythms (Campbell, 1993). Despite earlier contradictory findings, the conventional overnight rise in melatonin has been found in pigs (see Bubenik et al., 200 and Tast et al 2001a, 2001b) which is similar to European wild boar (Tast et al., 2001a). As in other seasonal breeders, this rise relays information on daylength to the brain (Peltoniemi, Tast and Love, 2000). Thus, pigs have the capacity to be photoresponsive and the potential to respond physically and behaviourally to changes in daylength.

Melatonin secretion is reduced by different wavelengths of light in different species, suggesting that care should be taken in provision of different light spectra, both overnight and in the evening. In rats, (typically nocturnal) red light suppresses melatonin synthesis (Poeggeler et al., 1995), but in humans, blue and green suppress melatonin, and red does not (Morita and Tokura, 1996), in rabbits (activity commencing at dusk), increases in blue and decreases in yellow intensity promote activity (Nuboer et al 1983). In pigs, red-light rearing produces the same results as dark-rearing, including similar

pineal gland development, suggesting that this light source is not perceived as "light" by the pig (Wheelhouse and Hacker, 1981). Tast et al., (2001b) found that melatonin cycles were measurable in pigs with photoperiods of 40 lux.

Supplementary melatonin can be beneficial in reducing existing stomach ulcers, and prevalence of ulcers (Bubenik et al., 1998; Ayles et al., 1999). This raises the possibility that use of a "correct" dark period, i.e. dark enough and long enough for optimal melatonin production can benefit health, and strengthens the argument for a dark period being as important as a light period.

The following section considers the effects of (artificial) lighting on all stages of pig production. Where information is available, these issues will be considered in terms of intensity or illuminance, photoperiod, changes in photoperiod, and spectrum. Clark (1981) notes that seasonality is related to photoperiod, not to quanta of light received i.e. a short photoperiod is not offset by increased illuminance.

The change from pre-test to test conditions is a key issue which is often overlooked; this affects perceived changes in photoperiod and illuminance which will also affect pigs' performance and physiology under the test conditions; this issue is also emphasized by Clark (1981). For example, moving pigs to 12L from 8L will be responded to as an increased/long daylength, but from 16L pre-test conditions, 12L will be perceived as a decreasing/short day. Pre-test conditions are rarely described; this is especially critical if animals have come from outdoor or naturally lit environments with varying photoperiods. Tast et al., 2001 initially stated that 1 week is sufficient to entrain pigs to a new circadian rhythm, but by 2005 commented that 6 weeks may be insufficient for pigs to acclimatise, so acclimatisation period to test lighting may also play a major role in interpretation of results. In view of some of the seasonal effects noted in wild boar, knowing the birth month and time of year of animals involved in seasonal studies would also be informative.

3. 1 Farrowing sows and piglets

Where gestating and lactating sows are housed under different illuminance regimes, it is often hard to distinguish whether the different lighting affects the sow directly and the piglets indirectly, or the piglets directly. Effects such as improved litter size will then affect measurements such as milk yield, suckling behaviour etc; lighting treatment *per se* does not affect these factors.

3.1.1   Sows and piglets – Illuminance
Sows under lower illuminances (2-6 lux and 10 lux; Komarov and Jurkov 1973a; 1973b) produced lighter and fewer piglets than sows under 70-100 lux. Illuminance was associated with position within the farrowing house during this experiment, so it is possible that temperature and ventilation could be allied with the illuminances. Mutton (1987) found no difference in piglet birthweights, weaning weights, pre-weaning mortality or growth rate of piglets raised under four illuminances (from 40 to 583 lux) on an 18L:6D photoperiod. However, creep lighting was available to piglets in this study; piglets in high home pen illuminance were thought to be unable to distinguish creep light regions, with consequent increasing the risk of overlaying. It is possible that these experiments demonstrate a lower illuminance cut-off for sow and piglet welfare i.e. 2-10 lux contributes to poorer welfare than 40 to 583 lux. The effects of higher illuminances have not been reported in these circumstances; potentially, welfare may continue to increase with higher illuminances, or may decrease following an optimum within 40 – 583 lux.

Newborn piglets were shown to be able to distinguish between bright, dim and dark environments, preferring dim and dark to bright light. Illuminances were 11, 5.5 and 2.8 lux in the test compartments, with the start box described as darker; all three illuminances could therefore be described as dim, but piglets still showed a preference (Parfet and Gonyou, 1991)

3.1.2   Sows and piglets - Photoperiod

In wild boar, sows breed in late autumn, with piglets born in early spring at maximum food availability; shortening daylengths should therefore be a cue to breeding receptivity. Smaller gilts may delay breeding until spring (increasing daylengths), with piglets born during autumn (additional period of food abundance).

Piglets are shown to benefit from longer photoperiods (16L v 8L) with heavier, healthier piglets (still significantly different at 10 weeks of age), and more piglets per litter (Niekamp et al., 2006; Mabry, Coffey and Seerley 1983). Piglets under long daylengths showed more suckling activity; this in turn will affect properties of the milk, contributing to improved health and weight.

Cunningham (1981) showed that increasing photoperiod does not increase prolactin production in the sow, and it is likely that changes found in milk properties (e.g. higher milk solids concentration) are a result of more suckling activity by the piglets.

Neikamp et al., (2006) showed that beneficial effects of long photoperiod on the sow (16L) can affect piglet immune response at least until piglets were 21d old. Short day length during late gestation in the sow is thought to contribute to increased litter size and survivability of the piglets (Niekamp et al., 2006). Whilst Hälli et al., (2008) found little difference between short day (10L) and long day (14L) photoperiods on sows and farrowing parameters the main difficulty in interpreting these results is that external season showed stronger effects than test conditions, with lower farrowing rate during summer – suggesting test conditions may not have overridden external cues.

3.1.3   Sows and piglets - Changes in photoperiod

Increasing the number of hours of illumination per day (to 18h), thus mimicking a spring birth, could benefit piglets, resulting in improved bodyweight gain and "wellbeing" (Jurkov, 1982). Claus and Weiler (1985) showed that increasing the hours of light per day (up to 15-16 hours) had little effect on sow parameters, but increased suckling frequency of piglets and increased survival of low birthweight piglets. Again, provision of longer photoperiod is therefore linked to higher piglet suckling activity, affecting milk quality and production by the sow.

3.1.4   Sows and piglets - Spectrum

Whilst lower stress responses at weaning were found in piglets housed under natural light compared with artificial lighting, these environments also differed in illuminance and photoperiod (Cook et al., 1998). The authors also note that the differences in cortisol measurements may also be due to the different perceived time of day by the groups due to different onset of photoperiod.

3.2 Grower-finisher pigs

3.2.1   Grower-finisher pigs – Illuminance

Dureau et al., (1996) kept minipigs under continuous 2,500 lux for up to 12 weeks. One of the results obtained was that animals experiencing four or more weeks of continuous illuminance lost up to 20% body weight, indicating either behavioural disinclination to eat, possibly due to discomfort, or to stress associated with the extreme lighting conditions. Whilst these breeds of pigs are not commercially relevant, it shows the potential for suboptimal welfare under high illuminance levels and continuous lighting.

Growing pigs in a preference chamber showed no differentiation between illuminances of <4, 4, 40 and 400 lux when active, eating and drinking similarly (~1.16h per day) in all compartments (Taylor et al., 2006). Results from this study showed that the pigs preferred to dung in more brightly lit environments, probably as a result of resting in dimly lit ones. When pen layouts are being designed, it is therefore preferable to provide dimmer lighting over the resting area, and brighter over the dunging area to encourage the pigs to rest in dimmer areas – the effectiveness of this will depend on the illuminance levels provided.

3.2.2   Grower-finisher pigs – Photoperiod

Bruininx et al., (2002) showed that long photoperiod in weaned pigs (23L:1D) improved their food intake and energy metabolism, with similar findings by Claus and Weiler (1985). Better immune responses have been found in weaned pigs given longer daylengths (up to 18h) Yurkov 1985), alongside improved feed intake and average daily gain at 44 lux (Bruininx et al., 2002). Similar results were also found by Niekamp et al., (2006) with improved health and weight in 16L piglets still significantly different from 8L piglets at 10 weeks of age. Lay, Buchanan and Hausmann (1999) found that 24 day old newly weaned pigs were more active under continuous lighting than 12L:12D. However, the piglets showed higher levels of agnostic interactions, suggesting reduced welfare under these conditions (Rudnev and Jurkov, 1976). It has been demonstrated that the majority of weanling pigs did not start eating during the dark periods of the day, with 24L recommended immediately following weaning (Bruininx et al., 2001).

Legislation currently prohibits commercial rearing of pigs in continuous darkness, but its effects have previously been examined. Adam and Telaki (1971) found that pigs in complete darkness had improved weight gain and better feed conversion rate, but higher carcass fat content than pigs kept in 24 hour light, with similar results found by Braude et al., (1958) and Benkov (1971). However, the opposite was found by Hacker, King and Bearss (1974), with gilts in continuous darkness showing a lower daily gain than controls (12L:12D). If these results are comparable, then combining them suggests that 12L:12D gave better productivity results than 24D, which was better than 24L.

3.2.3   Grower-finisher pigs - Changes in photoperiod

Changes in photoperiod for growing pigs are under-reported, however findings from both gilts and boars will be relevant (see below).

3.2.4   Grower-finisher pigs - Spectrum

Effects of only one specific range of the spectrum on pigs' production parameters have been measured. Rearing under 65 lux red-light (Wheelhouse and Hacker, 1981) produced similar results to rearing under constant darkness (Bearss, Hacker and Batra, 1974), with heavier bodyweights and improved daily gain in these groups compared with 65 lux (UV), 500 lux (Cool white fluorescent) and 650 lux (daylight) on a 16L:8D schedule (Wheelhouse and Hacker, 1981). (The two 65 lux environments are unlikely to match in brightness due to variations in the range of wavelengths presented.) This result is likely to be due to the animals' reduced perception of red wavelengths; the pineal glands of the two groups developed similarly suggesting the effect was due to lack of perception of the light source (Wheelhouse and Hacker, 1981), confirmed behaviourally by pigs' difficulty in detecting 694nm light sources (Taylor, 2006).

3.3 Breeding gilts and sows

3.3.1   Breeding gilts and sows – Illuminance

Diekman and Green found no effect on the pattern of melatonin secretion in pre and post pubertal gilts housed under either artificial 700 lux lighting and open fronted housing (max 50,000 lux in full sunlight) (2 month acclimatisation period). Diekman and Hoagland (1983) found little effect of supplementary lighting (300 lux) on maturation of gilts; whereas exposure to boars had a significant effect.

3.3.2   Breeding gilts and sows - Photoperiod

There are contradictory findings on effects of photoperiod on reproductive success in gilts and sows. If domestic pigs follow wild boar reproductive patterns, sows should be more stimulated by short daylengths (autumn/winter breeders); however smaller gilts may however be stimulated by lengthening daylengths (spring breeding).

Page, Charuest and Dufour (1988) found that more gilts failed to maintain pregnancies under 4h dark regimes (ahemeral 4D:4L, 4D:16L compared with 16D:4L and 16D:16L) and higher culling rates (due to non-conception) occurred in gilts under 16L treatments. 4D and 16L are likely to be perceived as short night/long day, midsummer season rather than lengthening daylength. Conversely earlier studies found that the more darkness the gilts received per 24h (i.e. simulated short day, long night), including rearing under continuous darkness, the longer they took to reach puberty (Bearss, Hacker and Batra, 1974; Hacker, King and Smith, 1976; Ntunde and Hacker, 1977; Hacker, King, Ntunde and Narendran, 1979; Ntunde, Hacker and King, 1979). This may reflect the age at which these lighting regimes were applied to the animals, e.g. a young gilt in short-day conditions may be biologically incapable of reaching puberty in that season, so development may be delayed such that she is in better condition for the next year.

The differences may also be due to continued development of pigs; breeds in the 1970s and 1990s may have different physiological requirements, as well as taking different times to reach maturity. The 1970s studies also included "unnatural" night lengths (for native pig environments) and may thus have included environments to which the pig may not be adapted, whereas the 1990s studies used more natural daylengths. Diekman et al (1991) showed that gilts on short daylengths with supplemental melatonin (mimicking shorter daylengths) and therefore autumn/winter photoperiods reached puberty faster. Sohst (1997) found seasonal effects of lighting on gilts but not sows.

Temperature will also play a major role in reproductive success, and needs to be controlled or reported to allow separation from lighting effects.

In sows, long photoperiods (e.g. 16 L v 1L) (McGlone, Stansbury, Morrow and Tribble, 1987) or high illuminances (e.g. 400, 500 and 700 lux but not 50 lux (Mutton, 1987)) reduce the number of days to next oestrus from weaning. Even keeping sows in 24 h darkness has been shown to improve their conception rate compared with 8 and 16 h daylengths (Benkov, 1974). Continuous lighting resulted in sows staying in oestrus for longer than 12 or 0h light-regime sows, but did not affect the number of days to oestrus from weaning (Perera and Hacker, 1979).

Again, these findings will relate to a control group of animals – the lighting conditions under which these animals are kept will influence whether the test conditions are stimulatory or suppressive in comparison.

3.3.3 Breeding gilts and sows - Changes in photoperiod
Gilts take longer to reach puberty during the summer (Skinner et al., 1999; Peltoniemi et al., 1999) or long daylengths (McGlone et al., 1987), and reach puberty more rapidly under a regime of shortening daylengths (Paterson and Pearce, 1990). These are presumably larger/older gilts reacting to photoperiod as mature sows would, with shortening daylengths stimulating reproductive physiology for late autumn conditions. Claus and Weiler (1985) found that decreasing the photoperiod by 20 minutes per week removed the seasonal increase of wean to oestrus interval (5.7 days compared with 23.6 days in controls).

3.3.4 Breeding gilts and sows - Spectrum
Hannesson (1999) found no significant effects of four conventional spectra (High pressure sodium (HPS), Metal Halide (MH), HPS + MH and fluorescent, illuminance unstated)) on breeding success in gilts. All groups had similar proportions reaching puberty, similar age at puberty, ovulation rate and embryo survival. However, the authors noted that the low colour rendering properties of the HPS bulbs limited success in detecting changes in redness in the vulva, therefore limiting its application in breeding and farrowing housings.

3.4 Breeding boars

3.4.1 Breeding boars - Illuminance
No information available

3.4.2 Breeding boars - Photoperiod
No information available

3.4.3 Breeding boars - Changes in photoperiod
Studies on boars show that puberty is reached more rapidly under a regime of shortening daylength (Neupert et al., 1995). In mature boars (both domestic and wild), decreasing photoperiod and short daylengths leads to increase in plasma testosterone (Weiler et al., 1996; Andersson et al., 1998) and spermatogenesis (Andersson et al., 1998).

3.4.3.1 Boar taint

Wild pigs breed in late autumn, with a secondary rise in spring (April – Claus and Weiler, 1985). Boars show decrease in steroid production, sperm count, and libido in summer versus winter conditions. Lower levels of boar taint are found in pasture-reared animals; lighting conditions on pasture will not only show a wider range of illuminance levels (including much higher values) and photoperiods than housed conditions, but will also have a wider spectral range; however, many other differences between outdoor and indoor environments and husbandry factors may also affect this. Wild boar are considered to have significantly higher levels of boar taint than commercial breeds (Andersson et al., 2000), thus environmental factors (including light) are probably of minor importance (Zamaratskaia 2004). Different breeds (Xue et al., 1996; Zamaratskaia 2004) and individual sires (Hansen et al., 1995; Andersson et al., 2000) have different magnitudes of boar taint. Experiments aiming to demonstrate photoperiod effects rarely control illuminance levels and spectra, and could potentially be confounded by zeitgeber (especially from other pens potentially on different lighting regimes) as well as temperature effects on behaviour and physiology.

Boar are known to mature faster in increased scotoperiod, decreasing photoperiod conditions (autumn), so the obvious hypothesis is that keeping pigs under "autumn" lighting would accelerate puberty and boar taint, and that "spring" lighting would decelerate puberty and reduce boar taint.

3.4.4   Breeding boars – Illuminance
No information available

3.4.5   Breeding boars - Photoperiod
While Sancho et al., 2005 found lower reproductive capacity in boars kept under complete darkness compared with 24 h light and 12 h light. Sperm parameters did not always coincide with fertility, however the seasonal effects on sow fertility cannot be ruled out in this work; sows were inseminated from the 24L and 0L groups in October and December, but from 12L males in March and May.

3.4.6   Breeding boars - Changes in photoperiod
In general, decreasing (autumn) lighting regimes have been shown to stimulate several reproductive parameters in domestic and wild boar as predicted, e.g. testosterone level (Andersson et al., 1998; Weiler et al., 1996) and activity aggression and lesions (Frederiksen et al., 2006). In Weiler et al., (1996) the wild boar, the wild boar refused food for several weeks at the peak of testosterone production leading to 25% weight loss. Artificial lighting with changing photoperiods (1400 lux, both spring and autumn) resulted in lower weight of reproductive organs, lower skatole and lower lean meat compared with natural lighting – suggesting some effect of illuminance level or wavelengths (Andersson et al., 1998). Spring lighting (440 lux natural light) has also been shown to increase androstenone (Frederiksen et al., 2006).

Skatole levels were higher in winter than summer in entire males in the UK, Sweden and the Netherlands, but no change was found in Danish, French and Spanish pigs. Whilst androstenone levels were higher in winter in the Netherlands, androstenone levels decreased in the UK population (no changes in the other countries studied) (Walstra et al., 1999). The systems donating the pigs are not described, so photoperiod itself may not be relevant; seasonal changes to other environmental

factors may be more relevant, and different systems may be differentially affected by changes in weather, external temperature etc.

Whilst decreasing photoperiod i.e. autumn lighting does stimulate reproductive physiology and behaviour in boar, and hence boar taint parameters, it is only a small factor in comparison with genetics and housing conditions.

3.4.7 Seasonality and temperature

As well as photoperiod, temperature influences the reproductive success of the pig; high temperatures and long daylengths coincide, so it is difficult in a non-controlled environment to separate these factors. Skinner et al., (1999) showed that effects of heat stress on the sow reduce the survival rate in the litter, McGlone et al., (1987) showed high lactational weight loss in sows in high temperatures, and Love (1978) concluded that heat stress on the sow (and litter) was the major cause of seasonal infertility.

Summary - Seasonality and productivity

The domestic pig has seasonally influenced reproductive success, indicating that it is a short day breeder, but is not strictly seasonal, with most commercial herds farrowing at least twice a year. Photoperiod can therefore play a role in reproductive development and success in both males and females, and in piglet development, although this is rarely observed in commercial situations when temperature is controlled. The responses to daylength can be subtle, suggesting there may be wide variation in the underlying responsiveness of different breeds and populations. Temperature control could avoid losses due to heat stress, and light-proofing an environment would prevent the pigs experiencing changing light levels and photoperiods and so allow greater control over their reproductive cycle.

What can be concluded from the above information is that

1) *Piglets benefit from increasing or long daylengths (15-18 hours) (increasing suckling → heavier and larger weaned litters)*
2) *Long or lengthening daylengths (e.g. 16L or longer) increase food intake in grower/finishers*
3) *Short or decreasing daylengths decreased time taken to reach puberty in males and females, and for sows to return to oestrus; these daylengths could therefore be a useful tool in breeding facilities,*
4) *Short or decreasing daylengths should be avoided in finisher housing to reduce mounting activity, aggression and to reduce risk of boar taint.*

Implications

The wide range of findings and recommendations imply that either experimental set ups are not fully controlled, that maturation of the pig is not fully understood or that photoperiod is not a significant factor in reproduction of the pig. Whilst peer reviewed literature indicates predicted responses in some experiments, advice to farmers often contradicts this. Effects of lighting –(photoperiod, illuminance and spectrum) on grower-finisher pigs is under-reported, suggesting that there is little effect of lighting on production animals. The conflicting results of effects of lighting on breeding animals implies that either seasonality in the pig is very varied between populations (and ages), or that experimental set ups are overlooking key factors. Temperature is a more important factor than

lighting in seasonal infertility in the British climate, and genetics and housing have more effect than lighting on expression of boar taint.

Further work

If seasonality has a significant effect on productivity then further work needs to go into establishing the correct photopattern at different stages of production. An examination of existing longitudinal nationwide production data should give evidence on the effects of daylengths and season on production – with such a large dataset, analysis should separate the effects of temperature from photoperiod. These results would give an indication of how important photoperiod may be in commercial pig reproduction and whether further effort is needed to reduce effects of seasonality. Thorough analysis of the data should enable comparisons between light-proofed and naturally lit and outdoor populations, examine whether there are differences in gilt and sow reproduction by season, and whether there is an interaction between gilt age/weight and season affecting reproductive success. If photoperiod has a commercial effect, then further work needs to be done to determine the optimal photopattern for reproductive success. Experimental work still needs to be done to establish the correct level of darkness for pigs for optimal production and welfare, i.e. differences between photo and scotoperiods that are perceived physiologically and behaviourally by the pig to avoid providing an environment perceived as continuously lit. Illuminance and photoperiod for different ages of pigs have still to be established, but are likely to be of low priority.

4. WELFARE

Inappropriate lighting can have a range of deleterious effects on domesticated animals (Barber, 2003; Kristensen, 2004), with both direct and indirect effects on behaviour and physiology. Fonken et al., (2009) found that inappropriate lighting increased depression-like symptoms in mice. Inappropriate lighting may also contribute by interacting with existing problems caused by other factors e.g. pigs kept in both high ammonia concentration level and low illuminance (40 v 200 lux) showed higher stress response than those in control environments (O'Connor et al., 2010 (in press)).

4.1 Measuring welfare

Welfare can be measured in several ways, i) physiological measurements, such as immune response, or hormones; ii) productivity, e.g. weight gain or loss, growth rate, time to reach puberty, or time between successive gestations, size and survivability of litters (N.B. animals may have been specifically selected for enhanced production, which can mask welfare indicators); and iii) behaviours; reflected in gross terms in level of activity, or more specifically in performance of selected or key behaviours; and the qualitative performance of behaviours. More specific to lighting are the condition of the eye; size and anatomy; and vision and visually mediated behaviours.

All these factors may interlink, e.g. pain in the eyes can lead to raised cortisol levels, and behaviours such as reduced eating or lameness can result in reduced weight and development.

4.2 Physiology

Rudnev and Jurkov (1976) reported that piglets raised under 50 lux were healthier in terms of blood biochemistry and immune status than those raised under 10, 20, 40 and 120 lux. This research needs to be repeated for a wider age range of pigs and illuminances. Stressful environments provided for sows will also affect their piglets, i.e. sows with high adrenal response levels had lower antibody levels in both the plasma and colostrum, affecting piglet survival (Zanella, Broom and Mendl, 1991).

4.2.1   Cortisol

Pigs show an increase in cortisol level in response to acute and chronic stressors (Baldwin and Stephens, 1973; Parrott and Lloyd, 1995). Cortisol is a useful measure of stress in the pig caused by a wide range of chronic and acute stressors, both environmental and physical.

Cook et al., (1998 and 1999) found that piglets housed under either genuine natural lighting or an artificially recreated, natural spectrum had a lower baseline cortisol level than controls kept under standard artificial spectra. Whilst photoperiods were matched in the 1999 study, the illuminances were brighter under artificial light, so illuminance effects on cortisol cannot be ruled out. The natural-spectrum piglets showed lower peak cortisol responses to weaning, and the recreated natural-spectrum piglets showed lower cortisol responses to the additional challenges of handling and transport. Although the experiments aimed to study the effect of spectra on cortisol, it is also likely that they reflect differences due to illuminance, or range of illuminances, on stress in the pig.

4.2.2   Heart rate

Heart rate increases in response to fear and stress, although increases also occur due to exertion and excitement (Fraser and Broom, 1997). In farmed red deer, isolation under darkness resulted in lower initial heart rate than isolation under an illuminance of 200 lux, suggesting lower initial fear or

excitement associated with the environment (Pollard and Littlejohn, 1995). Small groups of deer also consistently selected the dimmer region when in an unfamiliar environment. Deer are regarded as a prey species, and comparatively flighty compared with pigs, but active in similar lighting levels (crepuscular); pigs under similar conditions may therefore be predicted to respond similarly. However, piglets held isolated in the dark showed a clear preference for a lit environment (Tanida et al., 1996), however this has not been repeated for older pigs or where preference for home pen lighting can be ruled out.

4.2.3   Summary - physiology

Response of the adreno-cortisol system is a useful indicator of stress in pigs, particularly chronic exposure to a "poor" environment. This form of measurement would lend itself to the study of suitable light environments for the pig, provided that confounding effects of circadian rhythm, feeding pattern etc are suitably controlled. However, welfare should not just be judged based on one measurement system - the pig is capable of indicating poor welfare in one way, but without effects on other systems, e.g. psychological stress, such as an unfamiliar environment, activates phosphorylase in the pig's heart without affecting the heart rate or blood pressure (Skinner, Beder and Entman, 1983).

4.3 Behavioural measures of animal welfare

Lighting can have both direct and indirect effects on animal behaviour. Behavioural measures should be interpreted with care, e.g. a pig may lie down more because it is relaxed and comfortable, or may be showing passive coping or learned helplessness (e.g. Erhard et al., 1999).

4.3.1   Activity

In general, increased photoperiod in pigs is associated with an increase in activity. Lower activity is reported in pigs raised under continuous darkness (Bearss, Hacker and Batra, 1974), compared with pigs raised under 12L:12D. Weaned pigs raised under 24L:0D showed higher overall levels of activity throughout the 24 hour period than controls under 12L:12D; however increased activity was attributed to more agonistic encounters and social stress, suggesting that this is a stressor (Lay, Buchanan and Hausmann, 1999). Van Putten (1980) was unable to demostrate that the behavioural repertoire of pigs, and indirectly their welfare, was affected by the presence or absence of light.

Piglets raised under 120 lux in an intermittent pattern (6(1L:3D)) showed higher levels of activity than those raised under a range of lower illuminances, however, immunological and biochemical analysis of the blood showed these animals were less healthy, indicating potentially poor welfare conditions (Rudnev and Jurkov, 1976). (Intermittent lighting conditions have rarely been studied in pigs reducing the opportunity for further comparisons.) Disturbance to pigs caused by lighting changes should therefore be avoided; less savaging behaviour was found when farrowing units were continually lit (illuminance unstated) (Harris and Gonyou, 2003). McKeon (2010) states that the practice of switching lights off when leaving the farrowing room should be avoided.

4.3.2   Specific behaviours
Some key behaviours or states are mentioned specifically:

4.3.2.1 Fear and anxiety

Fear is one of the "Five Freedoms" i.e. "all animals should be free from fear" (FAWC, 1992; DEFRA, 2007). Rats handled under red light are calmer and less flighty, similar to their behaviour when handled our housed in darkness (Fall, 1974; Azar, Sharp and Lawson 2008). Phillips and Lomas (2000) concluded that calves were more fearful under green light than under red or blue lights intended to be isoilluminant to the animals.

In rodents, occupation of lit and unlit compartments is used to indicate fear, with rodents spending little time in the lit compartment rather than the dark (Andersen et al., 2000b) unless treated with Diazepam to reduce fear (Costall et al., 1989). However, in pigs, this is less clear. Although 23/84 pigs showed a strong preference for the dark compartment, the others occupied the lit compartment for an average of 29.5% of available time, however Diazepam-treated pigs spent more time in the dark than the controls (Anderson et al., 2000b). Pigs may therefore have a less innate fear of being in a lit area than rodents, with Diazepam possibly affecting behaviour in a way other than reducing anxiety, e.g. inducing sleep.

4.3.2.2 Stereotypies

High levels of stereotypy performance are associated with poor welfare in the previous or current environment, and a number of stereotypies have been observed in pigs (Broom, Mendl and Zanella, 1995). Lighting may indirectly trigger stereotypy bouts in pigs, as an indication of the imminent arrival of or prevention of access to food e.g. tethered sows were observed to perform stereotypies associated with the beginning and end of the photoperiod (Wiepkema and Schouten, 1992). The actual behaviours performed are probably derived from foraging or feeding attempts associated with food presentation during daylight hours rather than triggered by the light *per se*. One stereotypy that could be linked to lighting is eye-rolling; this is found in calves in a visually barren environment, and is thought to be an attempt to gain visual stimulation, but has not been reported in pigs (Fraser and Broom, 1997).

4.3.2.3 Fighting

Fighting between pigs during mixing results in injury and stress, with commercial loss and reduced welfare (Fraser and Broom, 1997); the effects of light on this behaviour are contradictory. Christison (1996) did not find any differences between mixing at 5 or 100 lux, and application of opaque lenses to the pigs (reducing vision) did not affect formation of social groups (Jensen, 2002). This suggests that vision may not play a principal role in fighting or communication of signals around fighting, even though a range of visual signals exists (Jenson, 2002). Potentially the intense nature of the introductions, e.g. reduced flight space and inability of subordinate pigs to escape, makes these signals ineffective in commercial situations.

Work by Barnett et al., (1994 and 1996) however, found that introducing new pigs in the dark produced a result comparable with treating pigs with an anti-aggression drug, Amperozide, with fewer aggressive encounters upon introduction.

There are several explanations for these differences:

1) Christison's pigs were kept under a continuous environment of either 5 or 100 lux after mixing; continuous lighting in itself may have been unfamiliar to the test pigs, causing stress, or the

continuous nature of the lighting may have resulted in irritability in the pigs; either of these may have increased the likelihood of aggression.

2) Barnett's pigs were grouped not just in the dark, but *after* dark, i.e. at the end of the day, after a second feeding bout, when the pigs would normally be settling down to sleep e.g. Simonsen (1990). It may be the timing of the mixing that affected these results – the pigs were already satiated and preparing for rest, and thus were less likely to fight. Food provision *per se* did not affect incidence of fighting in Barnett's work, with controls including *ad lib* feeding after mixing.

4.3.2.4 Lameness
Whilst lameness is commonly reported in meat birds raised under inappropriate lighting the cyclical nature of the problem is well studied, and the underlying causes are unlikely to apply to pigs (Fraser and Broom, 1997). In hoof stock, lameness and illumination links are less clear: cattle walking in a dark corridor change their gait (Phillips et al., 2000). In an animal with such large pressures on its feet and legs, repeated walking in an unusual manner could potentially also lead to lameness. In practice, the animals may choose to avoid such situations (Phillips, Lomas and Arab, 1998). Observation of pigs' gait under different illuminances has not been similarly studied. Farm-based studies of illuminance provision and lameness in pigs are likely to be confounded by floor type.

4.3.2.5 Feeding
Cattle avoid eating in the dark, to the extent of reduced milk production, liveweight and body condition; coincident with raised cortisol (Phillips, Lomas and Arab, 1998), however feeding behaviour does not appear to be affected by illuminance in the pig, with feeding and weight gain still occurring in the dark (Adam and Telaki, 1971). Pigs given a choice of four illuminances (0.4, 4, 40 and 400 lux) ate for similar lengths of time in all four illuminances (Taylor et al., 2006). Piglets showed greater suckling frequency and better survival of low birthweight piglets when kept in increasing hours of light (Claus and Weiler 1985); Gadd (2008) suggests leaving lights on for the first 24h post weaning enables more submissive animals to begin feeding.

4.3.2.6 Porcine headaches?
In humans, inappropriate lighting contributes to eyestrain, headaches and migraine (Brundrett, 1974; Wilkins et al., 1989). Behavioural identification of these symptoms in humans is difficult for an observer; e.g. decrease in general activity level, increase in irritability, reaction to bright lights or loud noises, avoidance of bright lights, rubbing of the eyes or temples (Botney, 1981). Similar behaviours in other mammals could be used to identify headaches and eyestrain, if the behaviours are analogous, or self-medication could indicate underlying pain (e.g. Rennie, Kent and Molony, 2001; Colpaert et al., 2001).

4.3.3   Ocular pathologies
Suboptimal lighting can affect the development and function of the eye. In poultry, buphthalmia (enlarged eyes) can be found under continuous darkness, continuous high illuminance and under photoperiod systems with low illuminance (Gelatt, 1993). Buphthalmia affects vision, and is likely to be painful (Miller, 1995), affecting stress levels and behaviour.

Continuous high illuminance has also been shown to affect the mammalian eye; albino rats show rapid reduction in visual ability due to destruction of outer segments of the photoreceptors (Birch

and Jacobs, 1977), and even continuous low light levels induce retinal degeneration (Shear, O'Steen and Anderson, 1973). Paler irides enable more light to reach the retina than dark ones, hence albino animals, and animals with blue irides are likely to be more affected by illuminance than animals with dark (hazel / brown) irides (Birch and Jacobs, 1977; Shear, O'Steen and Anderson, 1977). Adult minipigs kept under continuous 2,500 lux (Dureau et al., 1996) showed outer nuclear layer thinning in the retina, and reduced and slow pupillary reflex to light (compared with controls kept at 1,000 lux, 12L:12D). These conditions have not been recreated for domestic pig breeds, but similar effects are likely to occur, probably to a lesser extent due to increased thickness of the eyelid, and fewer developmental problems in the eyes of commercial breeds.

Buphthalmia is not recorded in pigs, and it is suggested that the wide aperture for humour outflow may mean the pig's eye is incapable of becoming buphthalmic (De Geest, 1987; McMenamin and Steptoe, 1991). Few ophthalmological problems are found in the commercial pig (Gelatt, 1993), although miniature breeds have high incidences of membrane remnants etc, which may be related to inadequate development of the eye (Loget and Saint-Macary, 2000). Vitamin A deficiency will also affect eye development in piglets (Hale, 1935).

Different spectra of light can damage the eyes, e.g. Baumgart et al., (1993) noted that far red (wavelengths >2,000 nm) can cause corneal opacity, miosis and delayed cataracts in the human eye, and exposure to near infrared (>1,000 nm) can cause retinal burns. However, human neonates receiving far infrared from radiant warmers did not receive retinal burns or permanent injuries to the eye (Baumgart et al., 1993). Ultraviolet wavelengths are also harmful; UVc supplementation (200-280 nm) increased the incidence of conjunctivitis in domestic fowl (Barrott et al., 1951), however wavelengths of 310 – 390 nm did not result in eye abnormalities (Hogsette, Wilson and Semple-Rowland, 1997; Lewis and Morris, 1998). The red/infrared and UV sources used by Wheelhouse and Hacker (1981) did not damage the eyes of the pigs they housed.

4.4 Vision

Vision may be affected temporarily or permanently by the above conditions. Physical changes in the eye's shape will affect refraction, conceivably preventing light from focussing an image on the retina (Troilo et al., 1995). Providing inappropriate lighting for animals could therefore prevent them carrying out visual tasks. More subtle differences can also be revealed by rearing or testing animals under different lighting regimes and observing their abilities in operant visual tasks.

The photoreceptor damage induced in mini-pigs (Dureau et al., 1996) is likely to affect their vision. The reduced pupillary reflex will also affect the pig's vision; the poor response of the pupil is likely to be due to damage to the underlying retinal cells, which, in rats, has been shown to trigger pupil miosis (Young and Lund, 1998). Slow reaction of the pupil will allow further damage to the retina by over-exposure to high illuminances, and inadequate pupil contraction will also prevent the eye focussing correctly under different illuminances (Land and Nilsson, 2002).

Newborn animals are more susceptible to eye damage as the eye continues to develop after birth, and is therefore more sensitive to its surroundings. In chickens, visual deprivation induces axial elongation and myopia, and application of a number of methods from inadequate illuminance to visual occlusion show similar results (Troilo et al., 1995). Experiments on rhesus monkeys, tree-

shrews, and cats show that suturing the lid or rearing in the dark interfere with the normal development of emmetropization, with individuals becoming significantly hypermetropic compared with light-reared controls (Guyton, Greene and Scholz, 1989).

Dark-rearing of animals affects their visual development, e.g. dark-reared rabbits showed a reduced optokinetic response, with a nystagmus response to a rotating drum at only 2/3 of the drum rotation speed. In the first week after the end of dark-rearing, some recovery was seen in visual abilities, but little change occurred after that (Colewijn, 1977). Spectrum of the rearing environment has not been found to affect subsequent colour vision in animals; pigeons (Brenner, Nuboer and Schelvis, 1985), monkeys (Brenner, Cornelisson and Nuboer 1990) and treeshrews (Kelly and Petry, 1989; Petry and Kelly, 1991) raised under coloured lights (normally red) did not show differential development of the cone types.

Summary – Welfare

Inappropriate lighting can have a range of measurable effects on welfare. In young pigs, natural spectrum lighting and 50 lux illuminance lead to less physiological stress compared with10, 20, 40 and 120 lux. Continuous lighting reduces welfare by increasing agnostic behaviours, and at high illuminance (2500 lux) also affected the eye and led to weight loss; intermittent photopatterns also agitated pigs. Pigs are not fearful of light (unlike rodents). Fighting in pigs <u>may</u> be reduced by introducing pigs in darkness. Pigs will feed in a wide range of illuminances (from darkness to full sunlight).

Although many effects of inappropriate lighting have not been studied in the pigs, results from other mammals should be applicable, e.g. visual deprivation in young animals affects vision (acuity and optokinetic reflex) and can also affect eye development and focussing ability. The pig's eye is rarely found to have ophthalmic problems, but is also unlikely to be presented for study when they occur.

Implications
Inappropriate lighting can affect the welfare of pigs, but most practices with severe welfare implications (i.e. continuous darkness or continuous high illuminance) are prohibited by UK legislation. Pig behaviour seems to be affected very little by other experimental lighting factors; within reason and in terms of their welfare, pigs are highly tolerant of, or adapt to, artificial lighting regimes.

Further work
As mentioned earlier, optimal lighting for pigs to distinguish between individuals has not yet been established, and may help to reduce welfare issues such as fighting at mixing. Experiments to establish whether subtle effects such as position of lighting in a pen may also prove beneficial in commercial situations, e.g. can lighting be used in conjunction with ventilation to utilise pen layout optimally (separating dunging, feeding and lying areas, also whether choice of lighting environments within a pen can production benefits (animals show lower stress when they can choose between environments).

5. LEGISLATION IN THE EU AND ENGLAND RELATING TO LIGHTING FOR FARMED PIGS

5.1 EU Legislation

The current lighting legislation, which applies to animals in England, is described by the Welfare of Farmed Animals (England) regulations 2007(S.I. 2000 No. 1970), Schedule 1, paragraphs 3 and 16:

3. Where animals are kept in a building, adequate lighting (whether fixed or portable) shall be available to enable them to be thoroughly inspected at any time.

16. Animals kept in buildings shall not be kept without an appropriate period of rest from artificial lighting.

The specific legal requirements regarding pigs (all porcine stock, including farmed wild boar) are covered in the Welfare of Farmed Animals (England) (Amendment) Regulations 2003 (S.I. 2003 No. 299), Schedule 6, paragraph 8 which states that:

8. Where pigs are kept in an artificially lit building then lighting with an intensity of at least 40 lux shall be provided for a minimum period of 8 hours per day subject to paragraph 16 of Schedule 1 to these regulations (see above).

This legislation is derived from EU legislation, and based on the report of the EU's scientific veterinary committee (SVC, 1997). European Union Regulations were based on this report to produce Council Directive 2001/88/EC (EC, 2001.

5.2 DEFRA Codes of Recommendations

The DEFRA Welfare Code for pigs endorses this legislation, and also specifies and implies further qualities of the light environment (DEFRA 2003, 2007). Previously, lighting only had to be sufficient to allow pigs to be visible to the stock-keeper (DEFRA, 2000); this has now been amended to a minimum illuminance of 40 lux (DEFRA, 2003). Whilst inclusion of this specific illuminance allows a measurable standard rather than subjective perception, clear definitions for useful measurement of 40 lux are not provided e.g. location, height and orientation of the detector head will substantially affect the illuminance measured. Additionally, few farms are likely to have light meters, so this measurement is not easy for a farmer to provide accurately; descriptions such as number and type of light are misleading, and will depend on the building's height, reflectance and colour of walls, obstruction by walls etc. The origins of the minimum illuminance are based on the SVC (SVC 1997) statement that illuminances of 40-80 lux should be sufficient to allow pigs to see well enough to distinguish small objects and subtle visual signals, but this is not fully endorsed by later science. As demonstrated by Taylor (2006), the light source (incandescent or fluorescent) will affect how brightly the pigs perceive their environment, with fluorescent lighting perceived as nearly twice as bright as an incandescent environment when lux levels match, thus light source should be taken into account when specifying illuminance.

5.2.1   Justification behind the legislation - Allowing a pig to see other pigs
On a number of occasions in legislation and codes, the need for one pig to see other pigs is stated, e.g. in the DEFRA Codes of Recommendations for sow accommodation and boars. The SVC report (SVC, 1997) also states that "minimum light intensities should allow pigs to see well enough to

distinguish small objects and subtle visual signals". The actual illuminance needed for a pig to see another pig, or to distinguish small objects or subtle visual signals should therefore be determined. Recent work by Zonderland et al., (2008) found that pigs were only able to reliably distinguish Landolt Cs where the gaps were 30 to 40mm under 0.5 to 80 lux and hence be unlikely to perceive small visual objects under these illuminances. Similar work by Taylor (2006) concluded that pigs were unable to detect the difference between a 25cm Landolt C and a O (gap size 50mm) when presented at 1.6m but with uneven lighting (ranging from 36 to 229 lux at pig eye height). Therefore lighting at which pigs can distinguish small objects is still debatable. However, more relevant to pigs' ability to see other pigs is visual discrimination of conspecifics which has been performed at illuminances of 40, 70 and 200 lux at distances from 0 to 1m (Mcleman et al., 2008, and O'Conner et al., 2010 (in press))) showing that pigs can see and discriminate individuals under these conditions; illuminances below this have not been studied.

5.2.2   Tail biting

Lighting is also mentioned with respect to tail biting (DEFRA, 2003), in which excessive light levels are mentioned as a possible cause of outbreaks. This requirement is likely to be derived from the SVC report, which cited little experimental evidence for this though. Van Putten (1968) found a decrease in tail biting when pigs were housed in a warm environment under low lighting; temperature is known to have a major influence on tail biting. Van Putten (1980) also found an association between high illuminance fluorescent lighting and tail biting (Van Putten, 1980). However this may also reflect the probability that housing types with a higher probability of tail biting were also the types likely to use fluorescent lighting i.e. pigs under fluorescent lighting were more likely to be in fully slatted, artificially ventilated housing which are systems with higher likelihood of tail biting (Moinard, Sherwin et al., 2003; Taylor et al., 2010). The most likely factors of lighting that would affect pigs sufficiently to contribute to tail biting would be continuous, high intensity light, with continuous lighting shown to generate more active and more agonistic pigs (Lay, Buchannan, Hausman 1999). Chambers (pers comm.) notes that pigs housed under continuous illuminance (pens directly beneath the fluorescent tubes used as night lights for the building) had higher levels of tail biting than neighbouring pens.

5.2.3   Outdoor pigs

In outdoor pig systems, there is no specific provision made for artificial lighting, which provides a much wider range of illuminances and photoperiods than artificial environments. The Welfare of Farmed Animals (England) Regulations 2000 (S.I. 2000 No. 1870) and the Codes of recommendations (DEFRA, 2007) state that adequate shelter must be provided to protect the animals from extreme weather conditions, and specifically, that adequate shelter must be provided to protect the animals from the sun in summer. Although this provision is to decrease the risk of sun burn or heatstroke in the animals, it may also be beneficial in allowing them to avoid bright illuminances if they so choose.

5.3 Additional requirements – welfare schemes

In addition to compliance with EU and English legislation and the DEFRA Codes of Recommendations, farmers may also opt to join a national welfare assurance scheme for indoor-housed pigs, or a farm assurance scheme associated with a supermarket. The national schemes are Assured British Pigs (ABP, 2004), Genesis QA (Genesis 2008), Quality Meat Scotland (QMS, 2005) and Freedom Food (the

RSPCA's welfare standards; Freedom Food, 2010). These schemes require adherence to additional regulations some of which are aimed at providing welfare standards above the legal minima.

The Freedom Food 2010 standards include the requirements that:

In each period of 24 hours, housed pigs must have access to an area that provides:

a) a period of at least eight hours continuous light with a minimum intensity of 50 lux intensity, except that this may be lowered to correspond with the duration of the natural daylight period at the time if this is shorter

b) a period of continuous darkness of at least six hours, except that this may be lowered to correspond with the duration of the natural darkness periods at the time if this is shorter.

(For information; 50 lux is bright enough to allow a person of normal sight to read standard newspaper print)

Freedom Food therefore places greater importance on natural photoperiods and range of photoperiods than legislation. Their requirements are similar to Yurkov's conclusion that finisher pigs need at least 50 lux for 8-10 hours per day to support growth and body defence mechanisms (Yurkov 1985).

Assured British Pigs (ABP, 2004) requires that:

Pigs shall not be kept in permanent darkness, but be allowed access to either natural or artificial light equivalent to the period of light normally available between 09:00 and 17:00 hours, each day. Light shall be of a sufficient intensity to allow newspaper print to be read.

QMS standards for management, stock-keepership and welfare, including lighting, do not extend beyond the legislation and welfare Code (QMS, 2005).

The reference to reading newspaper print under the illuminance supplied (Freedom Food, 2010; ABP, 2004) at least provides a guide to the farmer as to what is expected in the lighting provided A few drawbacks of this are that the measure is subjective, and is unlikely to be carried out at pig-eye height, which is where the illuminance is most relevant. It will also be complicated by the length of time taken by the eye to adapt to illuminances inside a pig house, especially if coming inside from a bright outdoor environment.**5.4 Darkness**

Use of the term "darkness", both in Freedom Food (2010) and ABP (2004) and in the "dark periods" mentioned by the SVC is not further specified, which leaves it open to subjective interpretation. Natural night-time illuminances range from 0.001 to 0.1 lux (Electro Optical Industries, 2000), and it is probable that these levels are implied in use of the term "darkness", but this should be further specified, and checked according to effects that temporal provision of these illuminances may have on pig welfare, specifically optical and reproductive parameters. In one lighting treatment of Chokoe et al., (2009), the dark period of one group of sows ranged from 0-30 lux. Work by Taylor 2006 found that pigs chose to sleep (for the most hours per 24 hour period, and for longer bouts) in the darkest compartment (0.4 lux) when given a choice of four environments (0.4 lux, 4 lux, 40 lux, 400 lux), but darker environments were not provided for comparison. If the dark period is not dark enough, this

may affect whether the light and dark periods are differentiated physiologically and behaviourally by the animals.

5.5 International regulations

Other EU countries stipulate lighting beyond current EU legislation: Austria requires pigs to have access to daylight if there is no outdoor access, Belgium and Sweden both require that natural daylight is provided; Germany requires that pigs are housed under 80 lux for at least 8 hours per day and that they have access to daylight (Wageningen, 2010). Access to daylight is required "through wall or roof" for Belgium, Germany and Austria; Sweden requires daylight provision via windows. The code of accepted farming practice for the State of Victoria, Australia, states that pigs have a basic need for light during daylight hours, and that sufficient lighting should be available when required to enable proper inspection of the pigs (Minister for Agriculture, 1997). Wellington's code of recommendations (New Zealand) suggests an illuminance of at least 20 lux in enclosed buildings to allow pigs to find food and water, with artificial light available for adequate inspection (≥ 50 lux) (AWAC, 1999). It also states that "in general, light should be available in all buildings at daylight intensity for normal, seasonal, day light hours." This statement is ambiguous; presumably, during normal (outdoor) daylight hours, lighting should be provided of at least 20 lux as suggested earlier. Supplying artificial light at an illuminance equal to natural daylight is unlikely to be achieved with normal farm lighting.

Other countries specify additional lighting requirements at different points within swine housing. This is sensible for both the stock-keeper and the pigs, as different tasks will require different illuminances. Illuminances may also have different welfare outcomes for animals at different ages. The Canada Plan Service recommends 107-161 lux for housing animals during breeding and in farrowing rooms, a minimum of 53 lux in gestation housing, and 53-107 lux in nursery housing (CPS, 2003).

5.6 Experimental animals

5.6.1   EU regulations

Pigs have an increasingly important role as research animals, and this is reflected in provision of specific regulations for their housing. The EC working party recommendations for lighting state that a diurnal cycle of light and dark with a minimum of 8 hours of light should be provided (Council of Europe, 2002). The light period should provide a minimum illuminance of 50 lux at the level of the animals, but a higher level of at least 250 lux should be available at times of inspection to enable all animals and pen facilities to be clearly seen, and any problems detected.

These statements cover the measurement and inspection illuminance procedures mentioned above, and are therefore much clearer to apply.

5.6.2   UK Home Office regulations

Current UK legislation for animals used in scientific procedures (Home Office, 1989) notes that most laboratory animals are either crepuscular or nocturnal (this therefore includes pigs) and that their eyes are adapted to dim light conditions. They suggest that 350-400 lux is adequate at bench level for routine activities, and that care may be required to avoid undesirably high levels in cages (and

presumably pens of larger species). They suggest that laboratory animals be kept under a 12L:12D cycle, but dawn and dusk periods are not specified for pigs.

Summary – Legislation in the EU and England relating to lighting for farmed pigs

Photoperiod and illuminance are currently included in English legislation, and are further clarified in DEFRA's Code of Recommendations and in welfare assurance schemes. Spectrum of lighting is not specified (which will affect pigs' perception of illuminance), nor is provision of a dawn or dusk light setting, although this is not ruled out under current legislation. Although specific minimum illuminances are given, there is little scientific evidence to back up the selected values; the range of minimum illuminances suggested also shows that there is no strong evidence for the recommendations. No maximum illuminances are suggested; whilst the illuminance of "natural" lighting may extend into tens of thousands of lux, pigs will be able to avoid this by seeking shade or shelter. Although legislation requires that pigs are provided with a period of darkness, there is no scientific evidence for the most suitable illuminance, and no guidance is given on what should be provided. The low number of regulations regarding lighting provision for pigs reflects not only the lack of welfare-specific research in this field (most is strictly production related), but also the belief that lighting has only a minor role in pig welfare.

Legislation implications for welfare and productivity
This summary raises a number of issues concerning current legislation for the provision of artificial lighting for pigs:
- *Improved specification of how to measure illuminance using a lux meter, or provision of an alternative system of measuring light.*
- *Further investigation into the most beneficial number of hours of illuminance provided, and more specifically, the number of hours of darkness.*
- *Definition of darkness(lux or other measurement)*
- *Specified illuminance should be re-examined in case of detrimental welfare effects; although pigs were active equally in 0.4, 4, 40 and 400 lux, this may only reflect short-term suitability.*
- *The current minimum of 40 lux needs to be further quantified according to the light source used – a higher irradiance is needed under incandescent sources than fluorescent ones to provide a matched illuminance to the pig (8 pig-lux incandescent ≈ 5 pig-lux fluorescent).*
- *The appropriate illuminance minimum (and maximum) needs to be re-examined to identify the original sources used in the experiments from which this recommendation was made and therefore to which spectrum the illuminance applies.*
- *Should dawn and dusk periods be recommended?*

Further work
Legislation should be updated regularly on the basis of up-to-date scientific findings to ensure that best practices for welfare are recommended.

SUITABILITY OF POULTRY LEDS FOR PIG KEEPING

The new bespoke LED lighting provided for the poultry industry differs from conventional lighting in a number of ways

1) LED bulbs rather than tungsten or fluorescent
   a. different energy consumption and heat output,
   b. different source size,
   c. opportunity to dim bulbs without effect on spectrum
   d. minimal flicker – unlike fluorescent tubes
2) Spectrum – tailored specifically to the spectral sensitivity of domestic fowl (Prescott and Wathes, 1999), with the red part of the spectrum decreased.

- **What effects are these differences likely to have on pig welfare, behaviour and productivity?**

1a. Provided that the LED bulbs are not intended to be used as a heat source (e.g. creep lighting) difference in heat output should not be an issue; heat output from light sources is not generally considered to contribute to heat production or issues such as overheating in finisher buildings; heat output from pigs is significantly higher. Reduced heat of bulbs may also be beneficial in reducing burnt-on dust on bulb surfaces, prolonging the active life of the bulbs.

Reduced energy consumption is unlikely to benefit pigs directly, but producers benefit by the reducing the cost of lighting the pig's environment, and pigs may benefit indirectly by redistribution of resources.

1b. Source size should not be an issue provided that the light environment created is constant (rather than a series of spotlights and shadows) and provided that glare/dazzle from bulbs is avoided. Discrete size of the LEDs may help to reduce physical damage to bulbs during building cleaning.

1c. Dimming bulbs may provide useful zeitgeibers for the animals and could also be used in conjunction with timing of food onset to reduce crowding at feeders (feed should be switched on before lighting). Little work has been done on dawn and dusk lighting for pigs.

1d. Flicker from fluorescent tubes is highly unlikely to be a concern to pigs when tubes are working correctly, however failing bulbs, with 50Hz flicker (visible to humans) will create a flickering light source in the pigs' environment and should be avoided. LED flicker modulation is minimal compared with the 100% modulation in fluorescent tubes.

2. **Spectrum.**

The spectrum of the poultry-bespoke LED is tailored to maximise the optical efficiency of poultry (i.e. no "extra" wavelengths that are not visible). Comparing the relative spectral sensitivities of poultry, humans and pigs, pigs are far less sensitive to wavelengths below 505nm (blue) than are poultry (humans intermediate), similarly sensitive from 505-545nm, and much less sensitive from 545 to 600nm. Pigs struggled to detect light sources above 600nm, whereas poultry and human spectral sensitivity curves showed a more gradual decrease in sensitivity up to 694nm (red).

The high proportion of blue wavelengths in the poultry LED output will make the source comparatively bright to pigs (brighter than tungsten output) as pigs are sensitive to this region of the spectrum. The 525-565nm output will also be strongly detected. Whilst the red end of the spectrum has been decreased in order to benefit poultry behaviour and welfare, this is not a region of the spectrum to which pigs are sensitive, so removing the red portion of the spectrum is unlikely to play a major role in the pigs' perception, behaviour or welfare. The LED output in the 400-565nm range, matched to poultry sensitivity, should produce a light source that the pigs see as bright compared with fluorescent and tungsten sources because a greater proportion of the emitted wavelengths are within the pig's spectral sensitivity range.

Spectrum and behaviour.

The success of the bespoke bulb with poultry is attributed to removal of the red part of the spectrum – reducing chickens' ability to see red stimuli in their environment, which are commonly cues for aggression. Chickens show an innate pupil response to red light, suggesting that the colour red is significant to the chicken (Barbur et al., 2002). The sight of blood is known to be a key stimulus for pecking behaviour in chickens (Barbur et al., 2002), but Jankevicius and Widowski (2002) showed that the red colour of tail models was not associated with preference to chew the models by pigs, hence that visual stimuli from blood are not a key factor in tail biting; pigs are far more likely to detect bloodied tails by smell than by vision. Whilst pigs use visual cues in communication these are not colour linked (predominantly shape and contrast (Oliver, 1993)), so reducing a colour from the spectrum is unlikely to affect their behaviour in this way. The spectral sensitivity work also suggests that reflectance of blood (Nakanishi and Izumimoto, 1971) is outside the main spectral detection of the pig – likely to appear as dark/black, as infra-red sources do to humans. Mullan (pers comm.) found that in a commercial pig keeping situation, a red-green colour blind observer found it hard to differentiate blood, scabs etc on a pig from dung, and pigs are likely to show similar inability.

Hannesson (1999) found little difference between standard spectra sources on productivity in the pig, but noted that the high pressure sodium source, with low colour rendering index made stock inspection difficult, with key changes such as reddening of the vulva harder to detect. HPS bulbs typically have a colour rendering index of 22-75, in comparison with incandescent bulbs at 100 (optimal spectrum for humans to see colours correctly) and "white" fluorescent tubes (52-73) (Williams 1999). HPS bulbs have a high proportion of output in the range from 550-650nm – (yellow/red) which is well within human detection, but pig sensitivity declines rapidly above 577nm (Taylor 2006).

Reducing the red component is therefore unlikely to provide any significant behavioural benefits for pigs, information in the red end of the spectrum does not appear to be of biological significance to them and is not linked with any key behaviours. The spectrum of the bespoke poultry LEDs is unlikely to be detrimental to pig productivity and welfare, but is also unlikely to be better suited to pig housing than standard commercial sources. Whilst the spectrum needs to be appropriate for the pig's vision, it should also be suitable stock-keepers' visual tasks which will affect welfare and productivity.

PIG BESPOKE LIGHTING

The key factors in tailoring practical LED spectra for pigs are:

1) Efficiency – providing light only within the visible range of the pig (maximum range 360-700nm, Taylor, 2006; Neitz and Jacobs 1989).

2) Reliance on wavelengths from 380 to 580nm to provide the bulk of perceived brightness; pigs' sensitivity declines rapidly outside these values although they will be perceived. For this reason sources should not be weighted towards the red end of the spectrum.

3) Pigs are behaviourally most sensitive to light at ~450nm, spectra centred on this value would therefore be perceived as bright by the pig (Taylor, 2006).

4) Avoidance of spectra with low colour rendering to human vision as colour cues are needed by stock-keepers in daily tasks affecting productivity and welfare.

These indicators point towards a spectrum more similar to daylight (within the visible spectrum). Work by Cook et al (1998, 1999) suggests that pigs housed under natural light and an artificially created natural spectrum environment showed lower stress responses (cortisol) to moving and handling than pigs under conventional artificial lighting. (The authors did note that cortisol measurement may have been affected by time of day – natural light animals would have different circadian rhythm due to different time of light onset, and may consequently have had cortisol measures taken at a different biological time of day.)

Whilst the two cone types in the pig are maximally sensitive to 439nm and 556nm (Neitz and Jacobs 1988) the electrophysiological method cannot determine the role that the information from each cone type provides – from the behavioural data ((Taylor 2006)it seems clear that the visual system of the pig is biased towards light detection by the 439nm (short wavelength) cone. A specific spectral peak (spike) around 439nm will therefore be readily detected by the pig, whereas a spike around 556nm would be less significant. Whilst the spectra of fluorescent sources is created by combining specific spectral spikes (acute peaks attributable to specific chemicals in the coating), natural daylight provides a much smoother power distribution graph. Smooth spectral distribution would reduce the risk of "hitting" or "missing" cone types with precise sensitivity, which would have a considerable effect on brightness perception of the source.

Chiao et al (2000) showed that the cone pairs of a species provide the optimal perception i.e. clearest image, of its natural environment; in a forest habitat this was not affected by illuminance. The spectrum of a typical wooded habitat (i.e. wild boar habitat) is shown by Prescott

With regard to human colour sensitivity – if the recommended spectrum for pig keeping is incompatible with human observation tasks (such as assessment of redness, detection of wounds rather than scrapes of dung), observation spectrum LEDs could potentially be added which would be unlikely to affect pigs' perception of their environment; onset of observation spectrum would be unlikely to startle the animals.

An additional feature of the proposed LED sources which may be beneficial is the ability to dim the sources (or to fade sources on and off). This feature could enable dawn and dusk lighting to be

trialled which has potential production and welfare implications in reducing competition for food by pigs at light onset, reducing the startle effect of light onset, and providing zeitgeiber for night time, allowing pigs to prepare. One alternative would be to use dawn and dusk periods provided solely by intensity changes (stepwise or gradual); and alternative would be to use spectral cues to indicate time changes. In rats, (typically nocturnal) red light suppresses melatonin synthesis (Poeggeler et al., 1995), i.e. red light provision stimulates activity onset whereas but in humans, blue and green light i.e. midday spectrum) suppress melatonin, and red does not (Morita and Tokura, 1996).In rabbits (activity commencing at dusk or afternoon), increases in blue and decreases in yellow intensity promote activity (Nuboer et al., 1983). Commercial pigs, including outdoor populations, are generally less active at night time, so decreasing the light intensity could be used to encourage resting behaviour (pigs also sleep more in dim/dark conditions (Taylor et al 2006). As with humans, bluer light will indicate midday conditions, with sunset perceived as a shift towards yellow and red wavelengths.

There is currently no argument for different spectra differentially affecting different ages of pigs or different points of pig production, however farrowing gilts and sows may benefit most from an environment perceived as secure i.e. mimicking their natural selection of a shelter constructed from foliage – likely to have low light intensity and with light in the middle range of the spectrum (greens). However – farrowing sows are also the ones requiring most intense observation by stockkeepers – addition of observation lighting (with minimal disturbance or startle to animals) may therefore also be required.

Two subtly different daytime spectra could therefore be trialled to examine whether these significantly affect the behaviour, welfare and production of the animals in comparison with conventional spectra at matched illuminances.

1) Pig daylight - a smooth spectral distribution curve with maximum output around 450nm, minimal output below 360nm and above 700nm)

2) Pig forest light – a relatively smooth spectral distribution curve with maximum output around 550nm, minimal output below 360nm and above 700nm.

An additional spectrum for dusk could also be examined (i.e. reduced blue, higher yellow); alternately dimmed daylight or forest light spectra may be sufficient to simulate dawn and dusk environments.

Figure 1. Spectra of natural daylight and forest environment
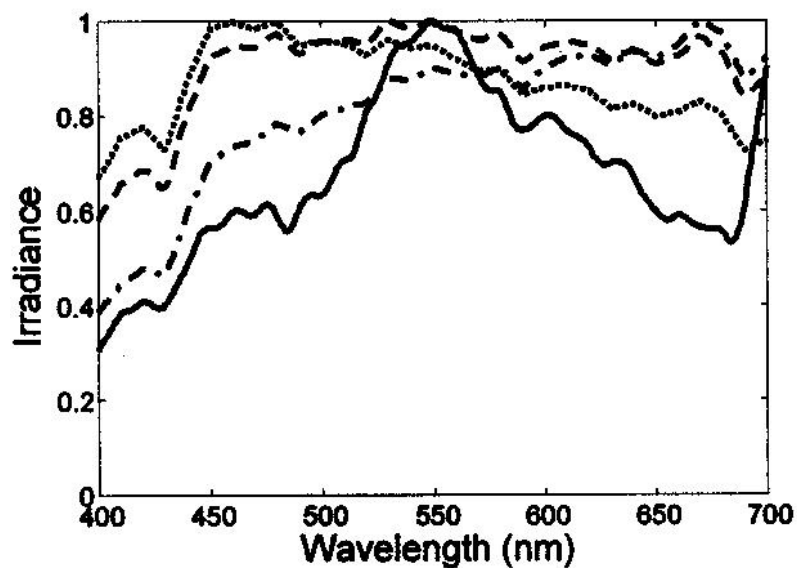
From Chiao et al 2000; Three standard daylight illuminant spectra (Wyszecki & Stiles, 1982), D75 (dotted line), D65 (dashed line), D55 (dot-dashed line), and one natural illuminant spectrum measured in temperate forest (solid line).

Based on the spectra provided by Chiao, approximate recommended spectra to trial for pig lighting are shown below.

Figure 2. Approximate trial pig spectra.
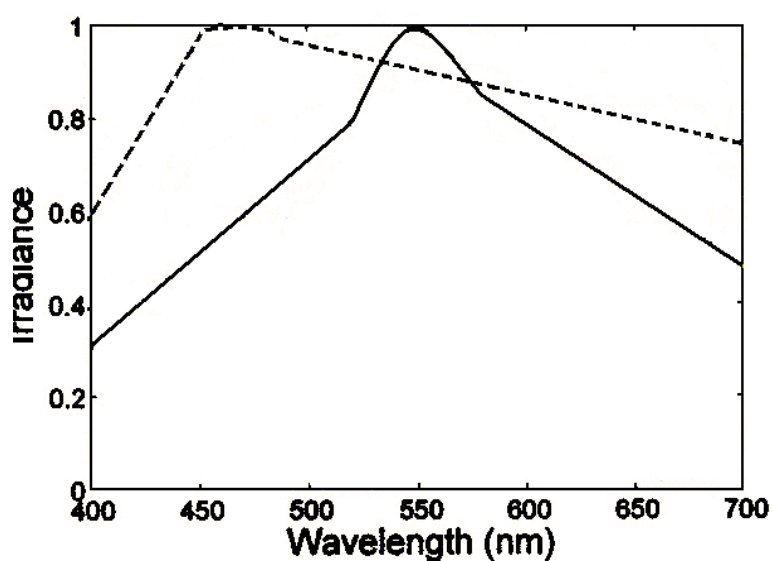
Pig daylight (dashed line), pig forest light (solid line)

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APPENDIX

Table 1. Acuity data calculated from eye anatomy

Species	Resolving power		Source
	Minutes of arc	cycles per degree	
Eagle	0.2	140	Reymond, 1985
Human	0.5	60	Pettigrew et al., 1998
Human	0.6	54.5	Taylor, 2006
Marmoset	1	30	Troilo, 1993
Marmoset	2.5	12	Pettigrew et al., 1998
Cat	2.5	12	Pettigrew et al., 1998
Pig	3.5	8.7	Taylor, 2006
Elephant	4.1	7.4	Stone and Halasz, 1989
Ferret	7.5	4	Pettigrew et al., 1998

Table 2. Acuity of animals determined by behavioural or electrophysiological methods

Species	Resolution (cycles / degree)	Method	Cues	Reference
Eagle	132-143	Behaviour		Reymond, 1985
Falcon	73	Behaviour		Reymond, 1987
Human	60	Behaviour	Snellen	Kolb, Fernandez and Nelson, 2005
Macaque	38	Behaviour	Grating	Merigan, 1990
Horse	18-23	Behaviour		Roberts, 1992; Timney and Keil, 1992
Dog	13.8-19.8	Behaviour	Landolt	Tanaka et al., 2000
Dog	4.3-11.6	Electrophys		Ofri, Dawson and Gelatt, 1993; Odom , Bromberg and Dawson, 1983
Cat	3.5-8.6	Behaviour, Electrophys	Vernier - grating, Grating	Belleville and Wilkinson, 1990; Pasternak, 1991
Pigeon	6.4	Behaviour		Gunturkun and Hahmann, 1994
Sheep	2.6, 2.9, 5.7	Behaviour	Landolt	Tanaka et al., 1995
Pig	0.5, 1.0, 1.1, 2.1	Behaviour	Landolt	Tanaka et al., 1998
Pig	0.9-0.03	Behaviour	Landolt	Zonderland et al., 2009
Cow	1.8	Behaviour	Landolt	Entsu, Dohi and Yamada, 1992
Rat	1.5	Behaviour [2]	square wave Gratings	Robinson, 2001
Rat	1	Behaviour	Grating	Prusky, West and Douglas, 2000
Mouse	0.5-0.6	Behaviour	Grating	Gianfranceschi, Fiorentini and Maffei, 1999
Goat[3]	0.4 - 0.5	Behaviour	X versus O	Blakeman and Friend, 1986
Mouse	0.5	Behaviour	Grating	Prusky, West and Douglas, 2000
Albino Rats	0.5	Behaviour	Grating	Prusky et al., 2002

[1] Optokinetic drum used; [2] Water maze used; [3] Acuity calculated from diameter of cues; if Snellen proportions were used, acuity could be up to five times this amount;

Table 3. Comparison of acuity values for several scales of measurement (adapted from Kolb, Fernandez and Nelson (2005) and Norton, Corliss and Bailey (2002)).

Human standards	Snellen Notation		Minimum angle of resolution (MAR) (minutes of arc)	Decimal
	Metric	Imperial		
	6/3.0	20/10	0.50	2.00
	6/3.8	20/12.5	0.63	1.58
Normal adult (MAR 0.82)	6/4.8	20/16	0.80	1.25
Standard	**6/6**	**20/20**	**1.00**	**1.00**
	6/7.5	20/25	1.25	0.80
	6/9.5	20/30	1.6	0.63
Unrestricted driving	6/12	20/40	2.0	0.50
	6/15	20/50	2.5	0.40
Moderate visual impairment (MAR 3.5)	6/19	20/60	3.2	0.32
	6/24	20/80	4.0	0.25
	6/30	20/100	5.0	0.20
	6/38	20/125	6.3	0.16
	6/48	20/160	8.0	0.13
Legal blindness	**6/60**	**20/200**	**10**	**0.10**
Profound visual impairment	6/150	20/250	25	0.04

Table 4. Sensitivities of cone types from representatives of different orders

Order	Species	Peak cone sensitivities (nm)	Reference
Lagomorphs (rabbits and hares)	Rabbit	425, 523	Nuboer and Moed, 1983
	Rabbit	425, 523	Nuboer, van Nuys, Wortel, 1983.
Rodents	Rat	359, 509-510	Jacobs, Neitz and Deegan, 1991
	guinea pig	429, 529	Jacobs, 1993
	Mouse	360, 509-512	Jacobs, Williams and Fenwick, 2004
	chimpanzee	430, 530, 560	Jacobs, Deegan and Moran, 1996
	owl monkey	460-480, 520-540	Jacobs, 1977
	Human	420, 534, 564	Bowmaker and Dartnell, 1980
Scandentia (tree shrews)	tree shrew	428, 555	Petry, 1990
		445, 560	Jacobs and Neitz, 1986
Carnivores	Cat	454, 561	Loop, Millican and Thomas 1987
		445-455, 555	Weinrich and Zrenner, 1983
	Dog	429-435, 555	Jacobs, 1993
Artiodactyls	Cow	431.5, 555.3	Jacobs, Deegan and Neitz, 1998
	Deer	450-460, 537-542	Jacobs et al., 1994
		450-460, 523-537	Jacobs, Deegan and Neitz, 1998
	Goat	443.3, 552.5	Jacobs, Deegan and Neitz, 1998
	Pig	439, 556	Neitz and Jacobs, 1989
		440.7, 556.7	Jacobs, Deegan and Neitz, 1998
	Sheep	445.4, 552.2	Jacobs, Deegan and Neitz, 1998
Perissodactyls	Horse	428, 539	Carroll et al., 2002

Table 5 – Summary of lighting and welfare of pigs

Pig group	Lighting factor	Details	Reference
Piglets	Illuminance	50 lux gave improved health and improved immune status v 10, 20, 40 and 120 lux	Rudnov and Jurkov 1976
Piglets	Spectrum / illuminance	Natural spectra at 32-121 lux and recreated natural spectra (139-215 lux) had lower cortisol levels than standard artificial spectrum (139-215 lux)	Cook et al., 1998, 1999
Minipigs	Photoperiod and illuminance	2,500 lux continuous lighting gave ocular damage and weight loss	Dureau et al., 1996
Growers	Photoperiod illuminance	Continuous darkness gave Increased weight gain, increased FCR, increased fat compared with 24 hour lighting	Adam and telaki 1971. Braude et al., 1958
Gilts	Photoperiod/ illuminance	Continuous darkness gave reduced daily gain	Hacker, King and Bearss 1974
Farrowing	Illuminance	2-6 lux gave reduced piglet weight and numbers compared with 70-100 lux	Komarov and Jurkov 1973a
Farrowing	Illuminance	70 lux gave increased piglet weight compared with 10 lux	Komarov and Jurkov 1973b
Piglets	Illuminance	No difference in birthweight, weaning weight, preweaning mortality or growth rates between 40 and 583 lux (18L:6D)	Mutton 1987
Rearing	Spectrum illuminance	65 lux red light gave heavier bodyweight and increased daily gain compared with 65 lux UV, 500 lux cool white and 650 lux daylight	Wheelhouse and Hacker 1981
Adult	Illuminance	No difference in fighting behaviour between 5 and 100 lux continuous lighting	Christison 1996
Weaners	Illuminance	Reduced fighting in darkness compared with light	Barnett 1994, 1996
Pigs	Illuminance	Preference for dark	Hacker Bearss and Forshaw 1973
Growing pigs	Illuminance, Photoperiod	16 hours light selected per 24 hours. (4-400 lux). Preference for 0.4 lux (sleeping/ resting)	Taylor et al., 2006
Piglets	Illuminance	Preferred light over dark	Tanida et al., 1996
Pigs	Illuminance photoperiod	Operant light selection – selected 72% (light (17h 17) 350 lux.	Baldwin and Meese 1977

APPENDIX - REFERENCES

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