The effect of supplementary ultraviolet wavelengths on the performance of broiler chickens

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ABSTRACT Qualities of the light environment, such as the spectral composition of light, have been shown to impact growth and performance of broiler chickens. UVA light is visible to broiler chickens, whereas UVB wavelengths promote endogenous vitamin D synthesis, which could support their rapid development. The aim of the current study was to investigate the impacts of supplementary UVA and UVB wavelengths on performance indicators of broiler chickens.

Day-old Ross 308 chicks (n = 638), reared to a target stocking density of 33 kg/m^2, were randomly assigned to 1 of 3 lighting treatments: A) White light emitting diode (**LED**) and supplementary UVA LED lighting (18-h photoperiod); B) White LED with supplementary UVA and UVB fluorescent lighting providing 30 μW/cm^2 UVB at bird level (lights on for 8 h of the total photoperiod to avoid overexposure of UVB); and C) White LED control group, representative of farm conditions (18-h photoperiod).

Mortality was recorded, and broiler chickens were individually weighed at 8, 15, 22, 27, and 34 D of age. Generalized linear models and nonlinear mixed effects models (Gompertz curve) were fitted to determine the effects of UV wavelengths on broiler mortality and growth performance.

UV did not impact breast or leg weight of broiler chickens but was associated with differences in mortality, growth, and end weight. Broiler chickens provided with UVA for the full 18-h photoperiod had slower initial growth than control broilers and a reduction in mortality. Results from male broilers reared with supplementary UVA + UVB for 8 h indicated they could reach finishing weights sooner than controls, which supports the potential for UVA + B to improve the growth performance of males.

Results suggest that the provision of supplementary UVA + UVB wavelengths may improve the performance of male broiler chickens. The reduction in mortality in the UVA only treatment may warrant further investigation. The inclusion of UV wavelengths within poultry lighting regimes represents a promising area of further study.

Key words: broiler, poultry lighting, ultraviolet wavelengths, broiler performance, broiler mortality

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INTRODUCTION

Despite superior color vision, hue discrimination, and motion detection, broiler chickens are typically kept in lighting conditions deemed suitable for humans. Environments tailored to poultry vision could lead to improvements in bird health, welfare, and performance by supporting the development of normal vision and the ability to carry out critical visual tasks (Prescott and Wathes, 1999). Three main parameters determine the light environment of a poultry shed: light intensity; photoperiod; and the wavelength composition or "color" of the light. The domestic chicken possesses tetrachromatic vision, and the wavelengths of light they are exposed to have been shown to influence their behavior (Kristensen et al., 2007) and productivity (Lewis and Morris, 2000).

There is growing interest in the applications of ultraviolet wavelengths within the poultry industry. Exposure to UVB wavelengths, within 280–315 nm, facilitates endogenous synthesis of vitamin D and has been associated with improved growth, increased body weight, and reduced incidence of tibial dyschondroplasia and rickets

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in male broilers (Edwards, 2003). UVB exposure also improved bone mineral density, egg production, and levels of vitamin D in the egg yolk of caged laying hens (Wei et al., 2020). Dietary supplementation of vitamin D metabolites cholecalciferol and hydroxycholecalciferol were shown to improve feed efficiency, increase final body weights, and increase breast meat yield in broiler chickens under a range of conditions (Yarger et al., 1995; Fritts and Waldroup, 2003; Fritts and Waldroup, 2005). Breast meat yield is thought to be increased through stimulating satellite cell activity (Hutton et al., 2014) and increasing protein synthesis (Vignale et al., 2015). UVB provision, therefore, may be a promising strategy for improving the growth of broilers while supporting their rapid skeletal development and reducing leg weakness, which is a key welfare and economic concern.

Domestic fowl can perceive UVA wavelengths as low as 360 nm (Prescott and Wathes, 1999; Osorio et al., 1999). UVA wavelengths, 315-400 nm, are typically absent from indoor poultry housing, though artificial UVA lighting has been shown to positively influence activity levels and the performance of comfort behaviors (Kristensen et al., 2007) and lower the fear responses of broilers (James et al., 2018). However, little research has been conducted to investigate the effects of UVA on the growth and performance of broiler chickens.

As lighting technology continues to advance, it is important to understand the impacts of wavelength composition on broiler performance. Light sources with different spectral compositions cannot be directly compared without adjustment for the spectral sensitivity of the domestic fowl, and many older studies may have inadvertently confounded the influences of wavelength composition with the influence of light intensity (Lewis and Morris, 2000). In addition to reduced fear and stress responses (Huth and Archer, 2015) and improved tibia breaking strength (Akşit et al., 2017), broiler chickens reared under light emitting diode (**LED**) light sources had better feed conversion ratios compared with those reared under compact fluorescent lights (Mendes et al., 2013) or standard fluorescent lights (Akşit et al., 2017).

A meta-analysis of older studies by Lewis and Morris (2000) noted the growth of broiler chickens under white and red light was similar, suggesting long wavelengths may suppress growth rather than shorter wavelengths promoting growth. Subsequently, the distinct spectral outputs of LED have provided a way to study the impacts of monochromatic light environments on broiler chicken performance more precisely. Green light was found to promote the growth of broiler chickens during early development, whereas blue light enhanced growth during the later stages of development (Rozenboim et al., 2004; Cao et al., 2008; Cao et al., 2012). Compared with monochromatic conditions, mixed green and blue wavelengths may further improve broiler performance (Yang et al., 2016).

Evidence suggests green and blue light found in UVA wavelengths promote the growth of broiler chickens by increasing satellite cell proliferation (Halevy et al., 1998) and stimulating testosterone secretion (Rozenboim et al., 2004; Cao et al., 2008). Further benefits of blue and green wavelengths in broiler chickens include enhanced cellular and humoral immune responses and alleviation of the stress responses through a reduction of circulating interleukin-1β (Xie et al., 2008).

Wavelength composition generally does not impact broiler mortality rates (Wabeck and Skoglund, 1974; Lewis and Morris 2000; Rozenboim et al., 2004; Cao et al., 2008; Mendes et al., 2013; Rogers et al., 2015), though green light was associated with higher mortality in female broilers aged under 7 wk (Proudfoot and Sefton, 1978) and lower mortality in broiler breeders between 10 and 40 wk old (Cave, 1990) compared with those reared under white light.

The aim of the current study was to evaluate the impact of supplementary UVA only or a combination of UVA and UVB wavelengths on the following performance indicators in broiler chickens: mortality rate, final weight, growth rate, and breast and leg weights. Light emitting diode were chosen as the primary light source in the current study as they are energy-efficient, eliminate exposure to mercury found in fluorescent bulbs, and offer opportunities to more precisely tailor the wavelength composition of the light environment (Yeh and Chung, 2009; Pimputkar et al., 2009). The supplementary UV wavelengths provided in the current study treatments alter the spectral profile of the light environment in relatively minor ways compared with the control condition. However, the excellent hue discrimination and color vision of birds may mean even minor adjustments to spectral composition may potentially influence the performance traits of broiler chickens.

The provision of UVB wavelengths, to enable endogenous vitamin D synthesis, is hypothesized to increase the growth and breast yield of broiler chickens. Based on the supposition that the addition of UVA wavelengths (in conjunction with a small increase of the amounts of visible blue light) affects broilers in similar ways observed under monochromatic short-wavelength conditions, UVA is also hypothesized to improve growth.

MATERIALS AND METHODS

The current study used 638 Ross 308 broiler chickens obtained from P D Hook Hatcheries Limited, UK, on hatch day. Chicks were from a 35 to 45-wk-old parent flock and received vaccinations for infectious bronchitis at the hatchery. On arrival chicks were weighed and randomly assigned to 3.4 × 2.5 m floor pen in 1 of 6 rooms (2 replicates per treatment, n = 106–107 chicks per room/ n = 212–213 chicks per lighting treatment). To allow for sufficient time to complete certain measures, such as dissections, arrival of the chicks was staggered, with room 1, 2, and 3 (Flock 1) arriving a week before room 4, 5, and 6 (Flock 2). Each room was temperature controlled and set to follow a commercial heating and humidity program. However, it was difficult to maintain humidity at the high levels to match this program (Appendix A).

Birds were fed *ad libitum* on a commercial wheat-based diet provided by ABN (AB Agri, Peterborough, UK) and reared on a bedding of wood shavings. Fresh bedding was added regularly if litter appeared wet. Each pen had a small bale of straw for enrichment purposes. The final stocking density reached by the end of the trial was a commercially representative 33 kg/m^2, based on a total useable floor area per pen of 7 m^2 after subtracting space for feeders, drinkers, and enrichment bales. All broilers were individually identified with wing tags at 7 D old.

All birds were individually placed in a large bucket and weighed using electronic scales to monitor their growth. Flock 1 were weighed at 8, 15, 22, 27, and 34 D old, and Flock 2 were weighed at 8, 15, 20 and 27 D old.

A sample of 6 birds per room (12 birds per condition) were culled at 9, 21, and 30 D old to assess their development. Final depletion took place over 5 D when birds were 35 (Flock 1 only), 41 (Flock 2 only), 42, 43, 44, and 45 D old. All birds were euthanized using an overdose of pentobarbital sodium via the intraperitoneal route for 9-day-old broilers and by intravenous wing vein injection for older birds. Final body weight was obtained after confirmation of death by cervical dislocation. All birds were sexed postmortem by the identification of testes or ovaries (n.Females = 293, n.Males = 287 n.Unsexed = 8), and the left and right legs were dissected at the hip and weighed along with the left and right *pectoralis major* (*p. major*) and *pectoralis minor* (*p. minor*) (n = 142 per condition). Mortalities and culls for health reasons (n = 50) were recorded as part of daily husbandry checks.

Standard biosecurity measures were in place governing entry of personnel, and the experiment was reviewed and authorized by the Animal Welfare and Ethics Reviewing Body at the University of Nottingham, UK.

Lighting Treatments

There were 3 treatments in the current experiment: A) UVA wavelengths but no UVB; B) including both UVA and UVB wavelengths; and the control (C) with no UV wavelengths, representative of commercial practice. Each treatment was replicated across 2 rooms, and the main light source used in all rooms for this experiment was the Agricultural Lighting Induction System (**ALIS**) which consisted of 4 x 8 Watt clip-on LED provided by Greengage Lighting Ltd. (Edinburgh, UK), installed 170 cm from the ground.

All rooms were also fitted with a single 18 watt 12% UVB D3+ T8 florescent light (Arcadia Products plc, Surrey, UK), in a reflector, powered by a high frequency 18 W electronic ballast (Komodo, Leicestershire, UK). The fluorescent lights provided the UVA and UVB wavelengths for treatment B and was suspended from a length of steel cable at a height of 50 cm from the ground to provide 30 μW/cm^2 of UVB at chick head height when measured with a UV meter (Solarmeter Model 6.2, Glenside, PA). The height of the fluorescent lamp was altered to maintain the same exposure of UVB as the chickens grew, and the corresponding lamp height was replicated across the other treatments.

It was necessary to fit these fluorescent lights in all rooms as they create a localized patch of higher light intensity with a spectral output distinct from the ALIS LED. However, in treatments A and C, the fluorescent lights were fitted with clear CON-TROL-CURE UV Blocking films (Epak Electronics, Somerset, UK). A single clip on UVA LED (Greengage Lighting Ltd., Edinburgh, UK) was added to the ALIS in treatment A to provide UVA wavelengths.

The ALIS system was controlled by an automated DTD (Dusk till Dawn) Lighting Processor Control (Greengage Lighting Ltd.), which incorporates 30 min of "dawn" and "dusk" dimming at either end of the programmed photoperiod. The scotoperiod was programmed to start at 11 pm as a single hour of darkness on the day the chicks arrived, increasing by an hour each night, until 6 h of consecutive darkness was achieved (11 pm–5 am). The fluorescent lights were controlled by separate mechanical timers (Maplin, Rotherham, UK) programmed to switch on between 5:30 to 9:30 am and 4:30 to 8:30 pm for a total of 8 h of the 18-h photoperiod. The fluorescent lights were not left on for the whole photoperiod to reduce the risk of overexposure of UVB (Moan et al., 2013; Yam and Kwok, 2014). However, this meant UVA was provided for the whole photoperiod of 18 h in treatment A (via the UVA LED), but only for 8 h in treatment B (via the fluorescent light with no filter). Further details of the spectral composition and light intensity of each treatment are described by James et al. (2018) which presents welfare data for this study.

Statistical Analysis

All broilers (n = 638) were assigned a binary outcome of 0 (culled at the end of the experiment) or 1 (mortality or culled for health reasons). A generalized linear model (**GLIM**) with binomial family (analogous to a logistic regression) was constructed to investigate the impact of multiple independent variables (age, flock, and lighting treatment) and interactions between them on the dependent variable of mortality. Sex could not be included as an independent variable as this was not recorded for all mortalities. This model and all subsequent analysis were conducted in R version 3.02 (R Core Team, 2013).

Nonlinear mixed effects models (**NLME**) were constructed to investigate the impact of multiple independent variables (flock and lighting treatment) on growth using weights (g) at 8, 15, 22, 27, and 34 D old (Flock 1) or 8, 15, 20, and 27 (Flock 2). Initial weights were recorded when chickens arrived but were not attributable to individuals as birds were not wing tagged at that point and were allowed a habituation period before this procedure occurred. There was, however, no difference in initial weights between the treatments (based on a linear model) and growth curves were modeled on the days 8 to 34 weight data. A number of growth models were tested to establish which would best fit the data, following guidance on best practice outlined in Paine et al. (2011) and following Wiseman and Lewis (1998). Models tested

Table 1. Frequency of mortalities and age of occurrence.

Treatment	Flock	Age (D) 0–7	8–14	15–25	26–35	35+	Total	%
Control	Flock 1	0	5	1	4	6	16	15
	Flock 2	2	1	0	5	2	10	9
	Total	2	6	1	9	8	26	12
UVA only	Flock 1	1	0	0	0	1	2	2
	Flock 2	3	0	2	0	0	5	5
	Total	4	0	2	0	1	7	3
UVA and UVB	Flock 1	2	0	2	3	2	9	8
	Flock 2	3	0	0	2	3	8	8
	Total	5	0	2	5	5	17	8
	Overall	11	6	5	14	14	50	8

Mortality of broiler chickens is shown for the lighting treatments and for each room, along with the percentage of mortalities.

included Logistic fit, 4 parameter logistic fit, Gompertz, linear fit with and without intercept, exponential, 2 and 3 parameter power laws. The models were implemented using nlme and mvtnorm packages and using functions provided in the supplementary material of Paine et al. (2011). The best-fitting model was selected for each sex, based on R-squared. Then fixed effects of Treatment and Flock were added to the model, and Bird ID was included as a random effect. The equations of models for different treatments were extracted from the nonlinear models and significant differences in the terms in the equation reported. Finally, we considered the age at which chickens would reach a weight of 2.2 kg, which is expected by 36 D in the Ross 308 performance handbook and is an end weight for some commercial farms. This was achieved using the parameters from the Gompertz growth curves.

Generalized linear models were constructed to investigate the impact of age, flock, and lighting treatment (independent variables) and interactions between them on end weight (g) and breast and leg weights (g) at 9, 21, 30, 35 (rooms 1, 2, 3 only), 37 (rooms 2 and 3 only), 41 (rooms 4,5, 6 only), 42, 43, 44, and 45 D old. Owing to the differences in growth curves of male and female broiler chickens both sexes were modeled separately.

For all models, fit was checked, as were assumptions of heteroskedasticity and normality of residuals where appropriate. Models were simplified as much as possible using backward elimination to exclude variables, based on whether a significant change in model fit (chi-square test). Uncorrected P-values are presented within text and figures and generally, α is considered to be 0.05; however, if applying a conservative Bonferroni correction, α would be 0.006. The test statistic for each fixed effect, based on z or t distributions as appropriate, and effective sample size are also presented. Effects of variables other than treatment are only reported for models where a lighting treatment effect was observed.

RESULTS

Mortality

Broiler chickens in the UVA only treatment had reduced mortality compared with the control treatment (GLIM: n = 638, z = -2.689, P = 0.007), though no difference was observed between the control and the UVA + UVB treatment (Table 1). There was also an effect of age, with mortality less likely to occur as broilers got older (GLIM: n = 638, z = -7.243, $P < 0.001$).

Weight Gain (Age 21–30)

The best fitting curves for weight gain was the Gompertz curve which fitted males (Figure 1A) and females (Figure 1B) separately with an R squared of 0.981 and 0.983, respectively. Gompertz curves are described by 3 parameters, the asymptote, the scale (rate of growth), and x0, the intercept. Males in the UVA (NLME: df=922, t = 2.47, P = 0.013) and UVA + UVB (t = 2.73, P = 0.007) treatments had higher asymptotes (indicating higher potential end weight) than control (see Table 2 for equations describing growth rate). The scale of growth curves for UVB treatments was not significantly different from control, although UVA had slower initial and then later faster growth (t = 3.71, $P < 0.001$). There was no difference in starting weight, as indicated by nonsignificance of the x0, intercept. Flock 2 had initial weights lighter than flock 1 (t = 5.01, $P < 0.001$). In females, UVB had a higher asymptote than control (NLME: df = , 851, t = 2.66, P = 0.008) and also had slower initial and later faster growth (t = 2.05, P = 0.041). UVB birds had a lower initial weight (t = 3.156, P = 0.002), which was also observed in UVA treatment (t = 3.92, $P < 0.001$) and in flock 2 being lighter than flock 1 (by 1.02 ± 0.01, t = 3.13, P = 0.002). Flock 2 also showed the catch-up growth, slower initially and faster later, that was observed in the UVB but not UVA treatment (t = 2.07, P = 0.039). These growth curves translate to an estimated 2 D earlier to reach a weight of 2.2 kg in the UVA + UVB treatment (30 D) compared with controls (32 D) for male chickens. For females, a weight of 2.2 kg would be reached 2 D earlier in UVA and UVA + UVB treatments (35 D) compared with control chickens (37 D).

End Weights (Age 21 to 45)

Owing to differences in the growth of male and female broilers, sexes were modeled separately. End weight significantly increased with age for both males

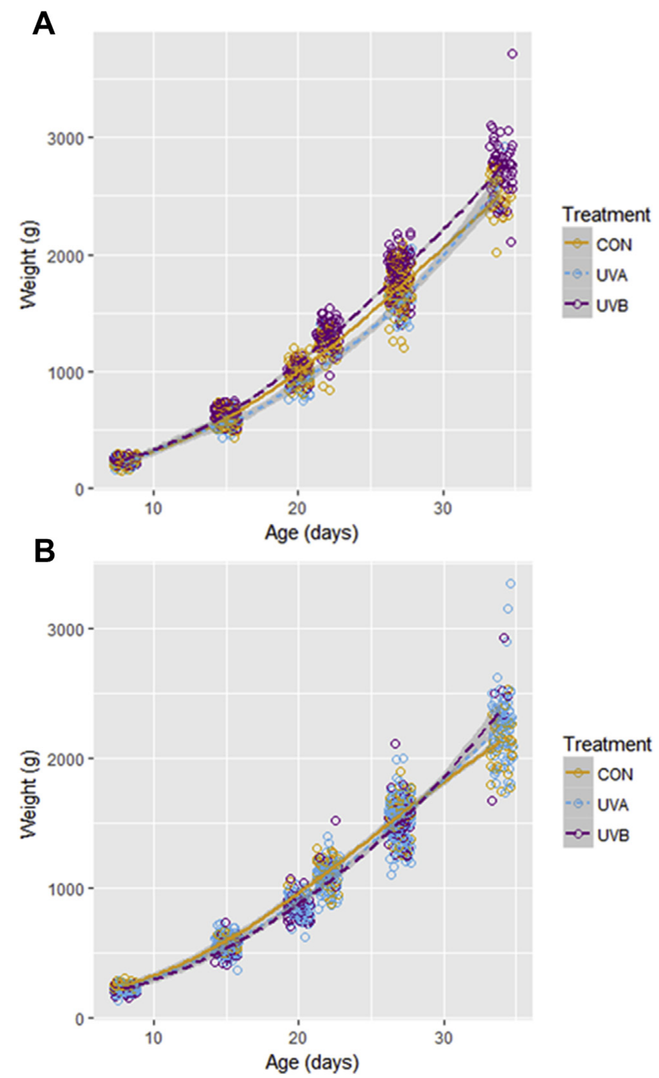

Figure 1. Growth curves for male (A) and female (B) broiler chickens with white LED light only (CON) white LED light + UVA LED (UVA) and white LED light with UVA + UVB wavelengths provided by a fluorescent light (UVB). Abbreviation: LED, light emitting diode.

(GLIM: df = 267, t = 37.731, $P < 0.001$) and females (GLIM: df = 275, t = 45.649, $P < 0.001$). Males in flock 2 were significantly lighter than flock 1 males (df = 267, t = −4.379, $P < 0.001$). Male broilers in the UVA + UVB treatment had heavier end weights overall than control broilers (GLIM: df = 267, t = 2.451, $P = 0.015$) (Figure 2), though there was also an interaction effect between age and treatment, where the age effect was reduced in UVA + UVB treated males (df = 267, t = −2.329, $P = 0.021$). There was a nonsignificant trend for females in the UVA treatment to have lighter end weights than control females (df = 275, t = −1.816, $P = 0.071$).

Breast and Leg Weights

Owing to significant differences in the growth curves of male and female broilers, sexes were modeled separately. Log values of all weights were used for statistical analysis to improve model fit. There was no significant effect of lighting treatment on mean broiler chicken breast (Table 3) or leg weights (Table 4).

DISCUSSION

The aim of the current study was to evaluate the impact of supplementary UVA and a combination of UVA and UVB wavelengths on performance of broilers chickens. The findings presented here suggest that UV wavelengths did not negatively impact breast weight or leg weights of male or female broiler chickens but could improve production performance with regard to mortality, growth, and end weight. Improvements in the growth rate of broilers in the UVA + UVB treated group indicate UV wavelengths may have the potential to improve the growth and performance, particularly for male broiler chickens. Broiler chickens in the UVA treated group had slower growth rates but reduced mortality, which could highlight potential benefits for broiler production.

Mortality

There was a 75% reduction in mortality for broilers provided with supplementary UVA for the full 18-h photoperiod compared with the control group with no UVA wavelengths. While it is not known whether this effect would hold in commercial conditions, reduced mortality would have important economic and welfare implications for the poultry industry, so these findings are worthy of further investigation. Similar reductions in mortality were not seen in birds provided with only 8 h of UVA + UVB. This could be because of the differences in the length of UVA exposure time or the more limited distribution of UV wavelengths across the

Table 2. Summary of Gompertz equations describing growth for each treatment and sex, with terms in the equation highlighted (in bold) which were significantly ($P < 0.05$) different from those in the control treatment for that sex.

Treatment	*Sex*	*Equation describing log weight in format: Log (Weight) = Asymptote * exp -(x 0 * exp -(scale *days since first weighed))*	*Terms in the equation significantly different from control*
Control	Male	8.55*exp-(0.475*exp-(0.062*Age))	
UVA		**8.81***exp-(0.476*exp-(**0.053***Age))	Asymptote, scale
UVA + UVB		**8.67***exp-(0.475*exp-(0.061*Age))	Asymptote
Control	Female	8.27*exp-(0.505*exp-(0.065*Age))	
UVA		8.67*exp-(**0.485***exp-(0.061*Age))	x0
UVA + UVB		**8.54***exp-(**0.481***exp-(**0.058***Age))	Asymptote, x0, scale

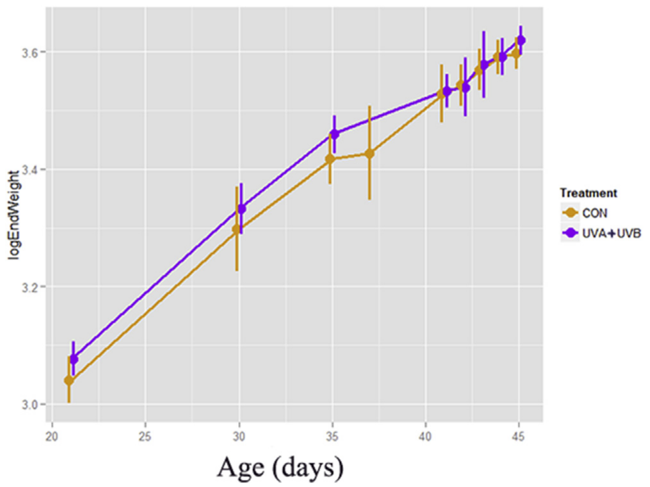

Figure 2. Log values of male broiler end weights (g) at 21, 30, 35, 37, 41, 42, 43, 44, and 45 D old. Results are shown for control and the UVA + UVB treatment only because of the low number of males assigned to the UVA only treatment.

UVA + UVB treatment room, where UV exposure was localized to an area under the fluorescent lamp. The possibility that UVB had a contrasting effect to UVA on mortality cannot be ruled out, though no studies currently support or refute this possibility.

The rapid weight gain of broiler chickens is linked to increased susceptibility to cardiac arrhythmia and sudden death syndrome, further highlighted by studies demonstrating early feed restriction decreases mortality in broilers (Bowes et al., 1988; Olkowski et al., 1997; Olkowski and Classen, 1998). Broilers in the UVA treated group had reduced initial growth, which may

Table 3. Mean and SD breast weights (g) of broiler chickens with and without UV supplementation.

Age (D)	Control						Total	SD
	N	Females	SD	n	Males	SD		
9	5	19	3.0	7	17	2.2	18	2.7
21	3	88	11.5	9	97	13.1	95	12.8
30	2	172	31.0	10	193	41.3	189	39.4
42	6	344	58.8	16	390	53.4	377	57.5
43	4	368	25.7	16	416	50.6	406	50.2
44	6	353	25.9	11	455	35.1	419	59.5
Age (D)	UVA only						Total	SD
	N	Females	SD	n	Males	SD		
9	6	16	2.9	6	18	3.1	17	2.9
21	10	80	9.7	2	98	22.6	83	13.1
30	12	173	17.4				173	17.4
42	23	329	36.6				329	36.6
43	20	357	52.1				358	52.1
44	19	349	50.4				349	50.4
Age (D)	UVA + UVB						Total	SD
	n	Females	SD	n	Males	SD		
9	8	17	3.7	4	17	2.5	17	2.8
21	3	88	8.9	9	106	10.0	101	12.3
30	3	193	10.8	9	224	32.6	216	31.4
42	7	326	23.1	15	384	41.6	365	45.3
43	5	342	26.6	15	416	37.3	398	47.6
44	5	329	43.0	12	460	40.4	421	73.1

Table 4. Mean and SD leg weights (g) of broiler chickens with and without UV supplementation.

Age (D)	Control						Total	SD
	n	Females	SD	n	Males	SD		
9	5	29	3.3	7	29	2.7	29	3.0
21	3	111	3.8	9	127	14.0	123	11.5
30	2	197	44.4	10	228	22.7	223	26.3
42	6	302	33.6	16	382	22.1	360	25.2
43	4	348	31.7	16	394	32.7	385	32.5
44	6	320	15.1	11	440	34.0	398	27.3
Age (D)	UVA only						Total	SD
	n	Females	SD	n	Males	SD		
9	6	25	2.9	6	29	4.1	27	3.5
21	10	102	12.5	2	137	3.6	108	11.0
30	12	193	13.1	0			193	13.1
42	23	301	23.4	0			301	23.4
43	20	326	28.9	0			326	28.9
44	19	320	36.9	0			320	36.9
Age (D)	UVA + UVB						Total	SD
	n	Females	SD	n	Males	SD		
9	8	27	3.9	4	29	3.1	28	3.6
21	3	110	7.9	9	138	9.5	131	9.1
30	3	206	24.4	9	240	28.8	232	27.7
42	7	307	11.8	15	385	48.2	360	36.6
43	5	303	16.7	15	410	37.5	383	32.3
44	5	325	42.9	12	435	26.8	403	31.5

have contributed to the observed reduction in mortality in this group. Stress also plays a key role in the pathogenesis of sudden death syndrome (Olkowski et al., 2008), and as UVA lighting has been found to reduce baseline stress levels in young chicks, increase exploratory behaviors (Maddocks et al., 2001), and reduce fearfulness (James et al. 2018), it is possible the reduced mortality in this lighting treatment could have been facilitated through reduced stress levels.

One of the limitations of the current study is the lack of males randomly allocated to the UVA only treatment from the hatchery. Male broiler chickens are generally more susceptible to sudden death syndrome (Olkowski and Classen, 1998), and as the sex of all mortalities during the trial was not recorded, it is not possible to say if this effect was observed in the current study. It is possible that the differences in mortality simply reflect the differences in sex ratios of the treatments. Postmortems were also not performed on all mortalities and would be an important consideration for any future investigation of the effects of UV wavelengths on mortality. Different sex ratios between our treatments may also have affected feeding behavior and feed competition; however, Avino et al. (2009) did not find any evidence of feed competition in a similar experimental set-up to this study.

Growth, Final Weights, and Breast and Leg Weights

Supplementary UVA and UVB wavelengths affected the weights and growth of broilers differently for males and females. The provision of localized patch of UVA and UVB for 8 h, using a fluorescent light source, increased the growth of male broilers throughout the 8 to 34 D growth period measured in this study. There was also an increase in end weights of broilers in the UVA + UVB treatment. Based on studies investigating vitamin D metabolites on broiler chickens (Yarger et al., 1995; Fritts and Waldroup, 2003; Fritts and Waldroup, 2005) and UVB light (Edwards, 2003), it was hypothesized that providing a combination of UVA and UVB for 8 h of the photoperiod would improve growth, end weights, and breast weight yield.

In the current study, improved growth was observed primarily in male broiler chickens, which is consistent with results obtained by Edwards (2003) (which only used male broiler chickens). In the females, the models indicated a different start weight (intercept) between treatments, although this was not evident from the day 1 weight data, which was not different between treatments. Thus, this is most likely an artefact of the modeling, where differences at day 8 (or subsequent days) between treatments could lead to the prediction of different earlier chick weights, although it is possible that there was a difference between treatments in the weight of day 1 chicks in females only as we did not record sex at this time. Differences between males and females may reflect characteristic sex differences between circulating hormone levels (Harvey et al., 1979; Scanes et al., 1984), which also regulate the hydroxylation of vitamin D in birds (Tanaka et al., 1976). If further studies confirm sex differences in the effects of UV lighting on growth, this could be capitalized upon in commercial poultry production.

The provision of only supplementary UVA wavelengths for the full 18-h photoperiod using an LED light source generally decreased the weight gain of male broiler chickens during the early stages of growth. However, female broilers had increased weight gain later in (between 27 and 34 D old) compared with control females, and this later improvement in weight gain appeared to compensate for the earlier slower growth, as there was no significant differences between the end weights throughout the growth period.

The earlier slower growth could be because of increased activity, which has been found to be promoted by UVA wavelengths in previous studies in laying hens and broilers (Jones et al., 2001; Maddocks et al., 2001; Kristensen et al., 2007; Ruis et al., 2010; Bailie et al., 2013).

Blue and green monochromatic or mixed color LED light treatments have been found to increase growth and breast muscle yields together with improved feed efficiency in broiler chickens (Rozenboim et al., 2004; Cao et al., 2008; Cao et al., 2012; Pan et al., 2014; Yang et al., 2016), yet these effects were not observed in the UVA only treatment of the current study, which mixed white and UVA LED light in addition to an increase in visible blue and violet wavelengths.

There were also no improvements in breast meat yield observed in either UV treated group despite other improvements in growth in the UVA + UVB treated group. There are a range of possible explanations for this effect. First, violet and ultraviolet wavelengths may have distinct impacts on young broiler chickens, and the effects of blue and green light may not be characteristic of all short wavelengths visible to broilers chickens. Second, a wide range of environmental, genetic, and nutritional factors influence the growth, performance, and carcass composition of broiler chickens, which may have variable interactions with lighting parameters. The studies that showed improved growth and breast yield using green and blue LED employed different husbandry strategies and broiler strains, some kept at much lower stocking densities than those used in commercial practice. The commercially representative stocking density (33 kgm^2) of the current study or use of a shorter photoperiod (18 h instead of 23 h) may have limited the potential for improved growth or breast meat yield compared with smaller scale trials (Dozier et al., 2005; Dozier et al., 2006; Lewis et al., 2009; Olanrewaju et al., 2018).

Interventions which improve aspects of broiler chicken performance may be economically favorable within commercial practice, but increased weight gain and growth rates can be associated with welfare concerns such as reduced walking ability (Su et al., 1999; Sørensen et al., 1999; Kestin et al., 2001; Kristensen et al., 2006), which prohibit the expression of normal behaviors (Weeks et al., 2000). In the current study, the ultraviolet supplementation improved performance indicators while simultaneously improving walking ability and reducing fearfulness (James et al., 2018). This supports growing evidence that ultraviolet wavelength supplementation may, therefore, provide benefits both to bird performance and welfare.

CONCLUSION

In conclusion, UV has potential to improve commercial performance through decreased mortality and improved growth for longer term health and end weight. There is no evidence that UV impacted leg and breast weight. Broiler chickens provided with UVA for the full 18-h photoperiod had slower initial growth than control broilers. However, this was also accompanied by a reduction in mortality which warrants further investigation. There was an increase in the growth of male broilers reared with supplementary UVA + UVB for 8 h, indicating the potential for UV to improve the growth performance of males, potentially reaching finishing weights sooner which is beneficial for production. The benefits which have been previously associated with green and blue monochromatic light environments were not observed in the current study which used mixed white and UVA LED. The use of UVA LED is a novel approach, which could potentially be implemented on a commercial scale. Further investigation into the impacts of LED light compositions that incorporate UV wavelengths, and are tailored to the visual capabilities of the chicken, are of further importance to improve bird performance and facilitate good welfare.

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SUPPLEMENTARY DATA

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