Project title	Protected Ornamentals: Assessing the suitability of energy saving bulbs for day extension and night break lighting.
Project number:	PC 296
Project leader:	Dr Steve Adams/Prof Brian Thomas, University of Warwick
Report:	Interim report, July 2010
Key staff:	Dr Veronica Valdes Mrs Jayne Akehurst Mrs Angela Hambidge Dr Debbie Wilson (report author)
Location of project:	Warwick HRI
Project coordinator:	Mr Colin Frampton Donaldsons Flowers Ltd, West Sussex.
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DISCLAIMER:

The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

[Researcher A Name]

[Position]

[Organisation]

Signature .... Date ....

[Researcher B Name]

[Position]

[Organisation]

Signature .... Date ....

Report authorised by:

[Organistion A's authority Name]

[Position]

[Organisation]

Signature .... Date ....

[Organisation B's authority Name]

[Position]

[Organisation]

Signature .... Date ....

CONTENTS

GROWER SUMMARY

Headline

Given the phase out of tungsten lamps announced by Defra, growers currently using tungsten lamps to either delay or promote flowering will have to find replacements, work to date indicates that compact fluorescent lamps may not prove to be adequate replacements in all cases. Further work is planned to examine how LED lighting might best be used to control flowering on a commercial scale.

Background and expected deliverables

Photoperiodic lighting can be used to promote flowering in long-day plants (LDP) and to delay or prevent flowering in short-day plants (SDP). Tungsten (T) lamps have traditionally been used for this purpose as they are cheap to purchase and have a suitable light quality. However, Defra have announced that 'inefficient' tungsten lamps will be phased out over the period Jan 2008 to Dec 2011 and higher wattage lamps are already becoming difficult to obtain. Furthermore, there is a desire from some growers to move away from tungsten lamps to minimise stretching which can occur as a consequence of the light spectrum. Consequently, there is an urgent need to assess the suitability of alternative lamps.

Perhaps the most obvious alternative to tungsten lamps, at least in the short term, is compact fluorescent (CF) lamps. However, these have a different light spectrum and so care is needed if planning to make this switch. Compact fluorescent lamps are typically warm-white, and when compared with tungsten lamps, they have a higher output in the green and yellow portions of the spectrum, and very little far-red.

It should be borne in mind that lamps that are sold as '100W equivalent' may be equivalent to a 100 W tungsten lamps in terms of what the human eye perceives (lux), but they are not equivalent for plants. To give a similar output of photosynthetically active radiation (PAR), a 100 W tungsten bulb will probably have to be replaced by 30-35 W of compact fluorescent lighting and the configuration of lamps, including light output and reflector design will need to be considered. Consequently switching from tungsten to compact fluorescent lamps might not be straightforward, even if the light spectrum proves appropriate. Furthermore, whilst tungsten lamps can be cycled for energy saving (often halving the number of hours that they are 'on'), there are drawbacks to doing this with compact fluorescent lamps.

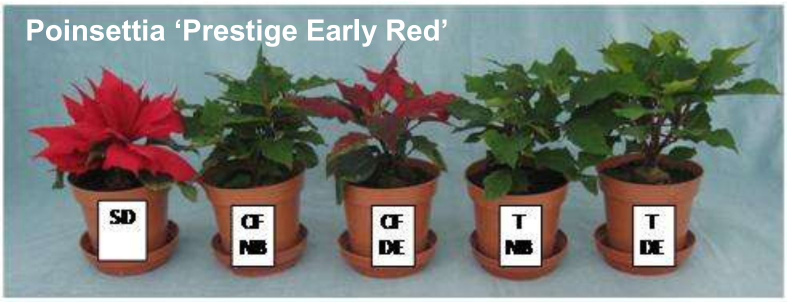
This project was therefore designed to examine the suitability of energy-saving lamps for daylength control by investigating flowering responses to light quality and quantity. The first part of the project, reported here, compared the use of tungsten and compact fluorescent lamps for a range of horticultural plant species to quantify responses in order to provide information towards making suitable recommendations for the replacement of tungsten lamps used to control photoperiod.

Summary of the project and main conclusions

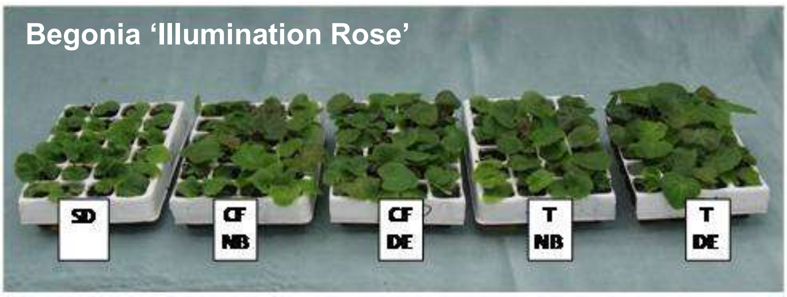
The effects of light level and light quality were examined in nine different species by growing plants in a suite of automated daylength controlled chambers (see photograph) where plants were exposed to 8 hours of daylight (from 08:00 h to 16:00 h) and then automatically transferred into light-tight chambers where the daylength was manipulated using tungsten or compact fluorescent lamps, or kept dark in the case of the short day treatment. Different light levels (1, 2.5 and 5 µmol/m^2/s) were used in the chambers. The effect of light level was also examined on fixed benches using light gradients (0.3 to around 9.3 µmol/m^2/s) to extend the natural short daylengths over winter. Both 8-hour day-extension lighting from 16:00 to 24:00 h, and 4-hour night-breaks (NB) from 22:00 h to 02:00 h were tested.

Chrysanthemum ('Tampico White'), plants grown under an 8-hour daylength (SD) budded and flowered rapidly (see photograph below), while all of the day extension (DE) and night break (NB) treatments remained vegetative until they had produced around 17-20 leaves on the side shoot; then they budded autonomously. Therefore, compact fluorescent (CF) lamps would appear to be safe for chrysanthemum. Interestingly even plants exposed to very low light levels (0.3 to 1 µmol/m^2/s) remained vegetative, suggesting that this cultivar might be more sensitive to light when compared with some of the older cultivars which were tested previously at the Glasshouse Crops Research Institute (GCRI).

Poinsettia ('Prestige Early Red') was also reasonably sensitive to compact fluorescent (CF) lamps. The plants grown under short days soon went red and had cyathia, while all of the long-day treatments initially remained green. Plants were kept for 26 weeks from pinching and over time some of the day extension (DE) and night break (NB) plants eventually showed some colour, although they did not develop fully red bract stars. There was considerable variability between plants, but colour was seen more frequently in the day extension (DE) treatment with compact fluorescent (CF) lamps. Plants appeared to be sensitive down to very low (0.3 µmol/m^2/s) light levels.

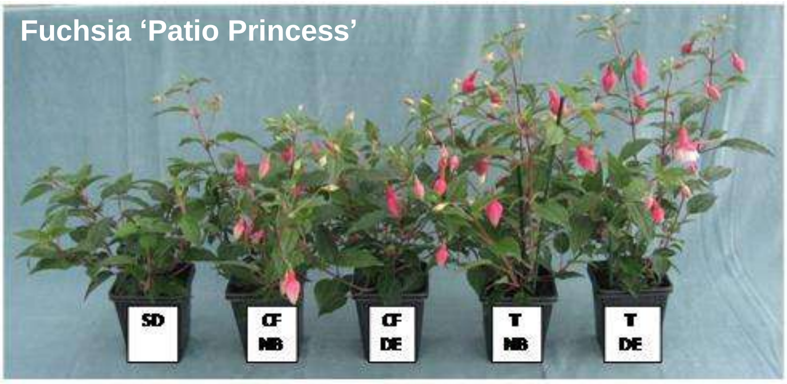


Non-stop begonia ('Illumination Rose') also responded well to compact fluorescent (CF) lamps, which were equally effective at delaying tuber formation and promoting shoot growth as tungsten (T) lamps. Plants appeared to be sensitive to very low (down to 0.3 µmol/m^2/s) light levels.

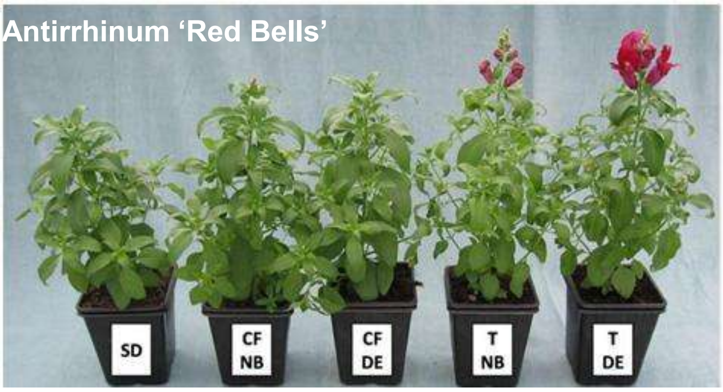


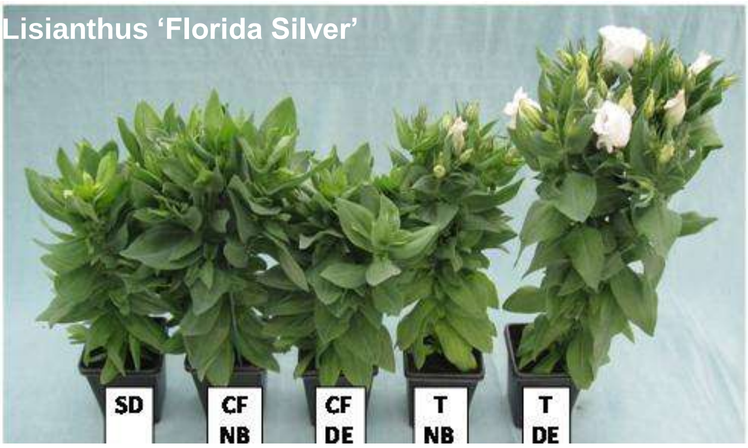
Christmas cactus ('Olga') was the only short day (SD) species tested where compact fluorescent (CF) lamps were less effective than tungsten (T) lamps. Flowering of these plants had been delayed by a tungsten (T) day extension (DE) treatment in commercial production before they were transferred to the experiments and this was also the most effective treatment for delaying flowering.

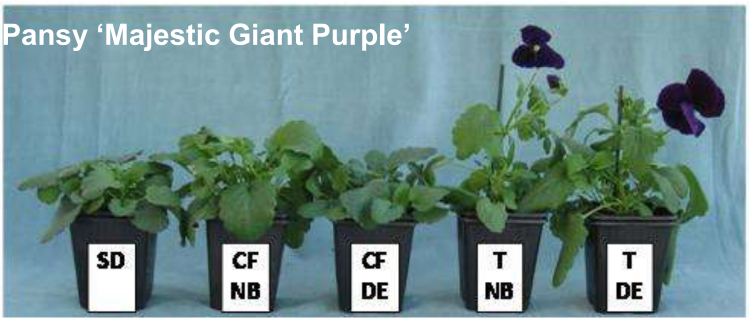
Fuchsia ('Patio Princess') plants grown under a continuous 8-hour daylength (i.e. SD) had no flower buds even at the end of the experiment (22 weeks after bud appearance in the long-day treatments) whereas the long day treatments budded rapidly. The day extension (DE) treatment with compact fluorescent (CF) lamps delayed flowering compared with the other long day treatments, but only by around 3 days. Plants appeared to be sensitive to very low (0.3 µmol/m^2/s) light levels.



Compact Fluorescent (CF) lamps tended to be less effective than tungsten (T) lamps for most of the long day plants that were tested. With **antirrhinum** ('Bells Red'), **lisianthus** ('Florida Silver' and 'Forever Blue') and **pansy** ('Majestic Giant Purple'), day extension (DE) lighting with compact fluorescent (CF) lamps proved ineffective, irrespective of the light level; plants flowered at a similar time to the short-day (SD) treatment. Night break (NB) lighting with compact fluorescent (CF) lamps was more effective, although it did not tend to hasten flowering as much as a tungsten (T) night break (NB). In the case of antirrhinum and lisianthus, plants budded sooner with an 8-hour tungsten (T) day extension (DE) than they did with a 4-h tungsten (T) night break (NB). Similar results were found across the light levels tested.

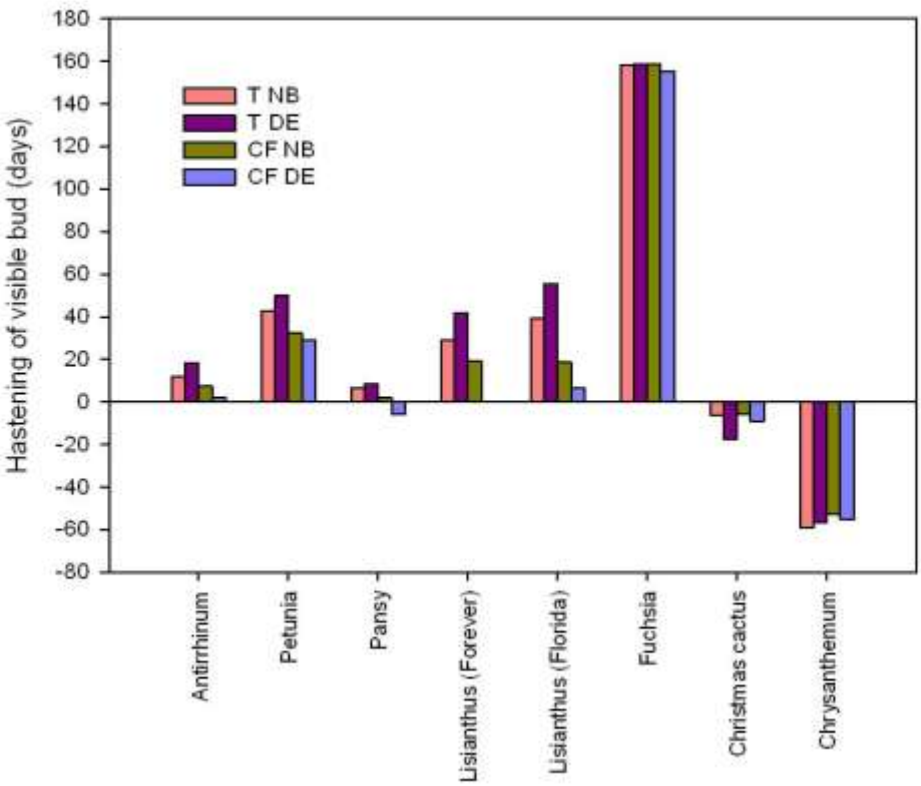






Day extension (DE) lighting with compact fluorescent (CF) lamps hastened flowering of **petunia** (‘Express Salmon’) when compared with the short day (SD) treatment. However, once again, these lamps were not as effective as tungsten (T), especially when used as a day extension (DE). Similar results were found across the light levels tested.

A cautious approach should be taken with regards to the replacement of tungsten with compact fluorescent lamps as just over half of the species tested did not respond effectively to the light spectrum from compact fluorescent lamps. This can be illustrated for those species that could be assessed on time to flowering in the figure below. The data in this figure represents time of bud appearance relative to that of the short day treatment (i.e. hastening of flowering) for a range of species. Hence for antirrhinum, flowering was 12 days earlier as a result of tungsten (T) night break (NB) compared with plants grown in short days and the negative numbers (e.g. all Christmas cactus treatments) indicate where the lighting treatments delayed flower bud appearance.



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These results applied even when the light level was increased to twice that of the current commercial norm. This is probably because the compact fluorescent (CF) lamps lack far-red light, which appears to be more important for day extension (DE) than night break (NB) lighting. Furthermore, while compact fluorescent (CF) lamps are a suitable replacement for tungsten (T) lamps in some species (e.g. chrysanthemum, poinsettia, fuchsia and begonias), there may be more efficient alternatives available soon.

Light–emitting diodes (LEDs) have advanced greatly and now provide a relatively efficient and robust alternative. They also have a much longer life expectancy than other lamp types, and this is not shortened by repeated cycling. While LEDs offer many advantages, high cost is currently an issue, although this is likely to come down over time. LED lamps can be manufactured to produce light of any given wavelength (colour), which is a big advantage for photoperiodic lighting if the plant requirements are known. The light output can be carefully selected to match the wavelengths that give optimal stimulation of plant light receptors.

Based on the results from this work, a combination of red (~660 nm) and far-red (~730 nm) light will probably give a good response for most species, although in some species, such as chrysanthemum, the far-red could be reduced, especially if stretching is a concern. The aim of subsequent experiments will be to test LED lamps of different wavelengths and compare their efficacy with tungsten lamps.

In summary the results suggest that compact fluorescent lamps could be safely used for chrysanthemums, poinsettias, fuchsia and begonias. However, with the other plant species tested more caution should be adopted as they did not respond to compact fluorescent lamps in the same way as they did with tungsten lamps. With Christmas cactus, a short day plant, a tungsten day extension was the most effective way of keeping plants vegetative. These plants had been kept vegetative prior to the start of the experiment using day extension lighting with tungsten lamps. Continuation of this treatment after the start of the experiment delayed bud appearance by a further 17 days (compared with the short day treatment). Whereas compact fluorescent lamps delayed bud appearance by 9 days (regardless of light level) when given as a day extension, and a compact fluorescent or tungsten night break delayed bud appearance by just 6 days. Therefore the phasing out of tungsten lamps could present a problem with this species.

Financial benefits

With tungsten lamps being phased out, growers face financial losses if they do not identify suitable alternatives. Taking Christmas cactus as an example, night break lighting is currently used in the UK to extend the marketing window of finished product. If the lighting installed to replace exiting tungsten bulbs did not effectively delay the crop, there would be an estimated loss of sales of UK production worth around £123K before penalty clauses issued for loss of sales by the retailer (up to another £140K).

Growers using tungsten lighting will have to switch over to alternatives as the phase out progresses. The current costs for compact fluorescent lamps are around £5.00 to £6.00 each compared with £1.00 to £1.20 for a tungsten bulb. Replacement LED lamps would be estimated to cost £40 per lamp (for the Philips flowering lamps designed for photoperiod control). Clearly there are efficiencies in life of bulbs and also energy use that need to be traded off against these capital costs but the increase in bulb costs emphasises the importance of identifying not only which type of lamp will be effective for the specie(s) grown but also that the set up of bulbs (i.e. number required per unit area which is determined by desired intensity amongst other factors) is efficient. The next phase of work will include a comparison of lamp types based on their efficiencies as well as spectral outputs which will provide the baseline data growers will need to devise sensible lighting strategies.

Action points for growers

- Where replacing tungsten bulbs is urgent, growers should test the most favourable alternative compact fluorescent strategies on a small scale with their own mix of plant varieties before implementing changes.

- Ideally growers should start to evaluate future strategies based on the results reported here but they should also consider the follow up work planned for this project, which is to evaluate how LED lighting might fit in with their future plans for controlling photoperiod.

SCIENCE SECTION

Introduction

Tungsten bulbs have traditionally been used for day-extension and night-break lighting as they are cheap to purchase and are rich in red and far-red light. However, Defra have announced that ‘inefficient’ tungsten bulbs will be phased out over the period Jan 2008 to Dec 2011. Furthermore, there is a desire from some growers to move away from tungsten lamps to minimise stretching due to the light quality. Consequently, there is an urgent need to assess the suitability of alternative lamps so that clear recommendations can be made for their use.

It is likely that tungsten lamps will largely be replaced with compact fluorescent lamps, however, lamps that are sold as ‘60W equivalent’ may be equivalent to a 60W tungsten bulb in terms of what the human eye perceives (lux), but they are not equivalent for plants. A number of recent HDC projects have used compact fluorescent lamps for day-extension and night-break lighting, without promoting a flowering response in what were thought to be long-day species.

This project is therefore examining the suitability of energy-saving lamps for daylength control by investigating flowering responses to light quality and quantity. Since species may vary in their response, a range of important horticultural species are being tested for their response to night-break and day-extension lighting given by tungsten and compact fluorescent lamps.

This report summarises the effects of light quality and irradiance which was examined in the first part of this project by growing plants in a suite of automated daylength controlled cabinets and by using light gradients. This work has been used to indicate the relative importance of light quality vs quantity (irradiance) which will be followed up in future experiments where other lamp types (e.g. LED lamps) will be compared with compact fluorescent and tungsten lamps for their efficiency and light quality.

Materials and Methods

Treatments

The influence of light quality was evaluated by examining response to either compact fluorescent or tungsten lamps. This was assessed by growing plants on trolleys in natural daylight in three glasshouse compartments between 08:00 h and 16:00 h GMT with plants transferred to light tight photoperiod cabinets outside of these hours and with the experiment spanning the period November to May 2009/10. Plants were exposed to long day (LD) lighting inside the cabinets either via a night break (NB) from 22:00 h to 02:00 h or as a day extension (DE) from 16:00 h to 24:00 h daily. Cabinets were actively vented when closed to maintain temperatures equivalent to the glasshouse compartment.

NB and DE treatments within the photoperiod compartments consisted of either tungsten (T) or compact fluorescent (CF) lamps types which were set to either 1 or 2.5 $\mu mol^{-1}m^{-2}s^{-1}$ as detailed in table 1 to ensure a fair comparison between lamp types and a further increase to 5 $\mu mol^{-1}m^{-2}s^{-1}$ was included for the CF lamps given the expectation that this lamp type may need to be delivered at a higher level to compensate for its different spectral output. The control, short day (SD), treatments consisted of cabinets which were closed but not lit.

Table 1. Summary of light quality treatments

Lamp	Treatment	Light levels ($\mu mol/m^2/s$)
Compact fluorescent (Long Days – LD)	Day extension (DE)	5
		2.5
		1
	Night break (NB)	5
		2.5
		1
Tungsten (Long Days – LD)	Day extension (DE)	2.5
	Night break (NB)	2.5
		1
	(Short Days – SD)	0

Experiments in photoperiod cabinets were supplemented by experiments on benches along which light gradients were set up with the primary aim of testing response to light level which diminished over an approximately linear gradient. A festoon was suspended above the bench with lamp spacing along the length of the bench varied in order to deliver a high (approximately 9.3 $\mu mol^{-1} m^{-2} s^{-1}$) light level at one end through to a minimal level (<0.3 $\mu mol^{-1} m^{-2} s^{-1}$) at the other end. As experiments were carried out during natural SD, gradients were effectively delivering LD treatments and were designed to examine threshold levels of light required to trigger a LD response. The CF and T lamp types were again compared in these experiments with benches housed in separate glasshouse compartments and screens used where required to eliminate light spill between treatments. The T treatment was delivered as NB in these light gradient experiments whilst DE (with lights on prior to sunset and off at 24:00h) and NB treatments (timing as in the photoperiod cabinets) were compared along identical gradients using CF lamps.

A summary of the experimental layout is given in figure 1. It was necessary to combine a mixture of bulbs in order to achieve the desired light levels in both the cabinets and along the light gradient benches. Appendix I details the combination of lamp types used for each treatment.

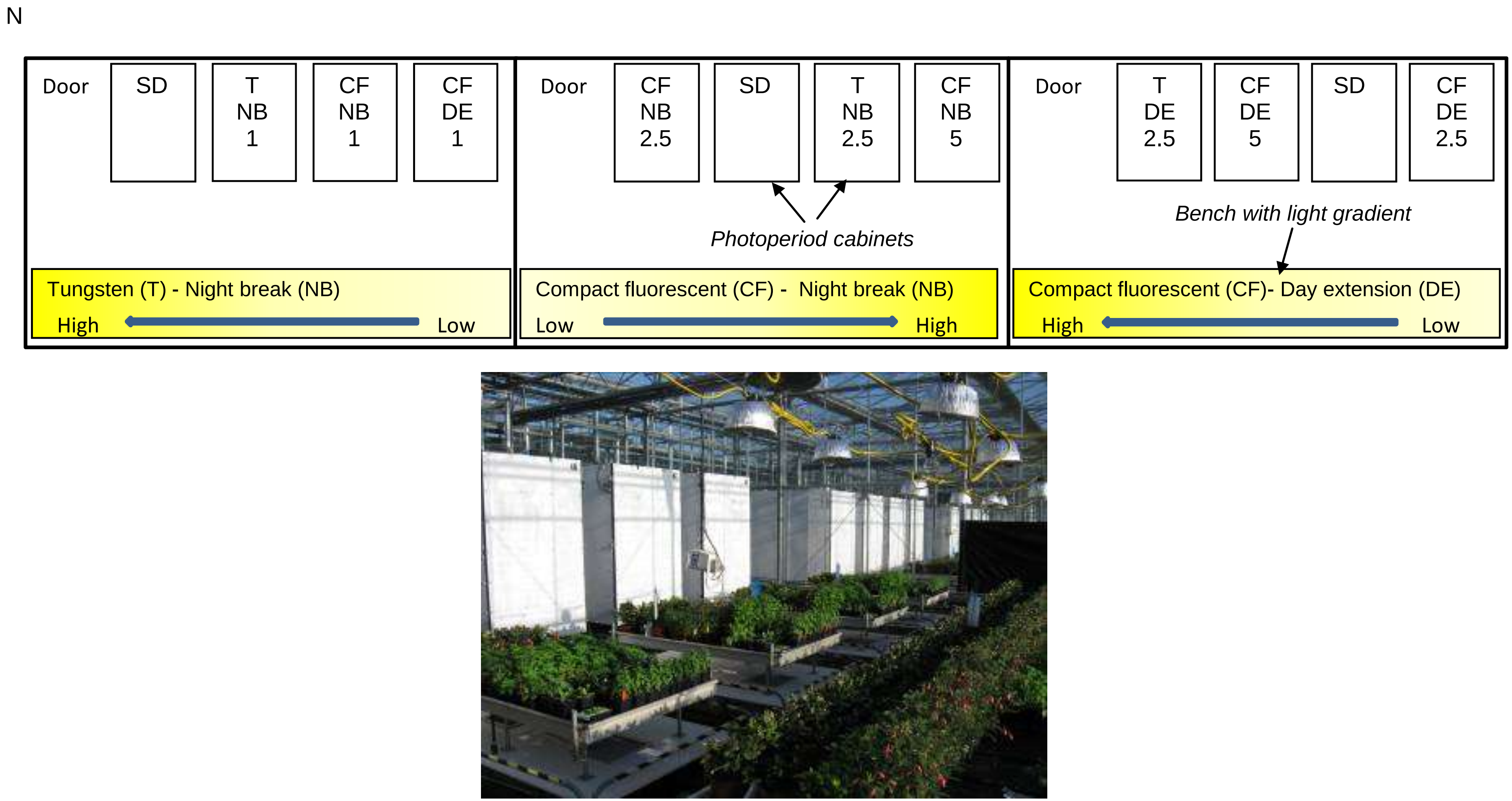


Figure 1. Layout of experiment

Plant raising

Species tested included both LD and SD response types with cultivars reflecting current commercial selections. Plants were either raised from seed or from rooted or unrooted cuttings according to standard practice and availability of young plants, two species were partially raised on commercial nurseries before being transferred to the experiment. As far as possible, plants were maintained in non-inductive conditions prior to starting treatments.

Species	**Cultivar**	**LDP or SDP**	**Source**	**Date into treatment**
Antirrhinum	Bells Red	LDP	Goldsmith Seeds (seed)	11/11/2009
Begonia	Illumination Rose	SDP (for tuber formation)	Bordon Hill Nursery (as part grown plugs)	08/12/2009
Christmas cactus	Olga	SDP	Opperman Plants (as part grown plants)	02/11/2009
Chrysanthemum	Tampico White	SDP	Yoder Toddington (unrooted cuttings)	30/11/2009
Fuchsia	Patio Princess	LDP	Botany Bay Nurseries via Young Plants (rooted cuttings)	02/11/2009
Lisianthus	Florida Silver and Forever Blue	LDP	Pan American (seed)	02/11/2009
Pansy	Majestic Giant Purple	LDP	Sakata (seed)	02/11/2009
Petunia	Express Salmon	LDP	Ball Colegrave (seed)	02/11/2009
Poinsettia	Prestige Early Red	SDP	Ecke Europe (rooted cuttings)	12/11/2009

All plants, potted at WHRI were grown in pots using Levington M2 when in treatments. Imidacloprid as Intercept was incorporated into the media of all WHRI potted plants except Fuchsia. Christmas cacti were potted in a specialist peat / perlite mix supplied by Bulrush to Opperman plants. Plant raising prior to starting treatments varied with species and is summarised below:

Christmas cacti were supplied as partially grown potted plants in week 39 and were grown on in a glasshouse compartment set to heat to 20°C day and 18°C night with venting at +2°C and tungsten night extension (at 2.5-2.6 $\mu mol^{-1}m^{-2}s^{-1}$) from 18:00 to 22:00 daily until being transferred into treatments. Begonia were also supplied as part grown plug plants in 240 plug trays and the plug trays were divided into 10 sections to provide an experimental unit (with 24 plants per unit) in each treatment.

Antirrhinum, Lisianthus, Pansy and Petunia seed were sown at Warwick HRI in 252 plug trays filled with Levington F2s compost in week 41, 36, 40 and 40 respectively. The trays were placed in a germination chamber until emergence (6 - 21 days), and then moved to a glasshouse compartment set to heat at 15°C day and 14°C night with venting at +2°C and under natural daylength until they were moved into treatments as detailed above. Seedlings were potted into 9 cm pots as they were transferred into treatments.

Rooted fuchsias were potted into 9 cm pots on receipt in week 42 and grown on in a glasshouse compartment set to heat at 15°C day and 14°C night with venting at +2°C and under natural daylength prior to being moved into treatments.

Poinsettias were potted up into 13 cm pots on receipt in week 44 and were kept in a glasshouse set to heat to 20°C day and 18°C night with venting at +2°C under LD conditions (tungsten night extension at 2.5-2.6 $\mu mol^{-1}m^{-2}s^{-1}$ from 18:00 to 22:00 initially and then with SONT lighting at around 25 $\mu mol^{-1}m^{-2}s^{-1}$ from 07:00 to 23:00 h from 05/11/09) to promote vegetative growth until ready to be pinched and moved into treatments.

Unrooted chrysanthemum cuttings were struck in week 46 at 5 cuttings to a 14D pot filled with Levington M2 compost mixed with Intercept. Cuttings were rooted under a polythene cover using bench heating to maintain a compost temperature of 21°C and with the glasshouse compartment set to heat at 18°C and vent at 24°C. Shade screens were set to a light threshold (350 W/m^2) during day period, and closed for energy saving dusk to dawn. Tungsten cyclic lighting was used from 23:00 until 04:15 (15 minutes on and 15 minutes off ending with lights on) while the sheets were in place. Sheets were removed after 9 days and lighting was then switched to SON/T lamps at 13.85 W/m² for 24 $h.d^{-1}$.

When plants moved into treatments all glasshouse compartments were set to heat at 17°C day and night with venting at +2°C. Compartments were continually monitored and adjustment as necessary to maintain equivalent achieved temperatures at all times.

Species were arranged in rows on trolleys and benches so as to minimise competition between the contrasting plant sizes. Eight pots per species were placed on each trolley for the photoperiod cabinets, and approximately 25 pots of Poinsettia, Chrysanthemum and Christmas cactus and 60 pots of the other species were placed on each bench as illustrated in figures 2 and 3. The sections of begonia plug plant trays were spaced out according to plant availability with 1 section on each photoperiod trolley and 6 sections along the light gradient benches.

Pots were irrigated to capillary matting with applications tailored to the demands of each species as much as possible. All species were fed with Peters Excel 15:5:15 Cal-Mag (with N at 100 g/l in the dilute feed).

Pest control was via a preventative programme of biologicals (*Aphidius, Encarsia, Phytoseiulus, Steinernema*, and *Amblyseius*) in addition to the 'Intercept' included in the growing medium. The disease control regime already established with the Christmas cacti which required spraying with Octave every 4 weeks for *Fusarium* and with Cuprokylt FL for bacterial soft rot was maintained. Other disease controls were applied as needed rather than as a preventative program. No growth regulators were used to ensure no interaction with the photomorphogenic responses to the daylength treatments applied.

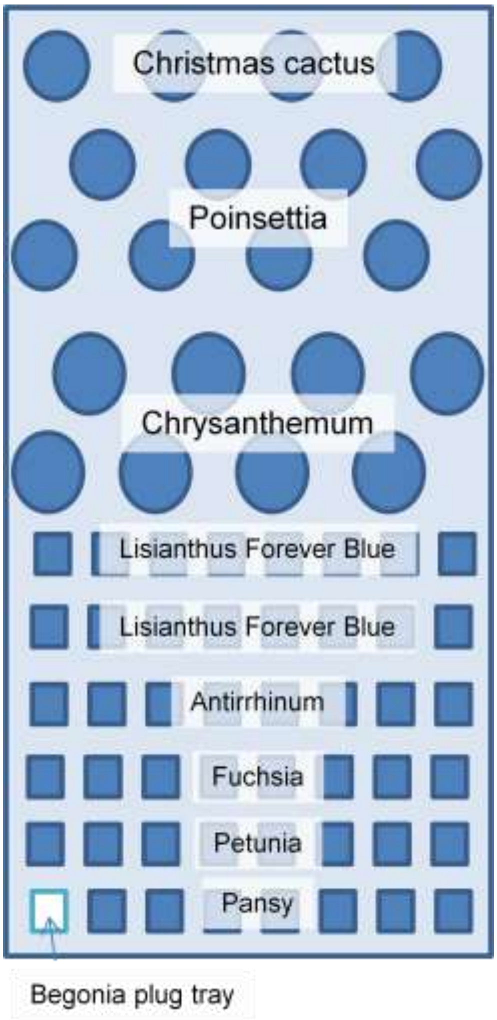


Figure 2. Layout plan for trolleys used in photoperiod cabinet experiments

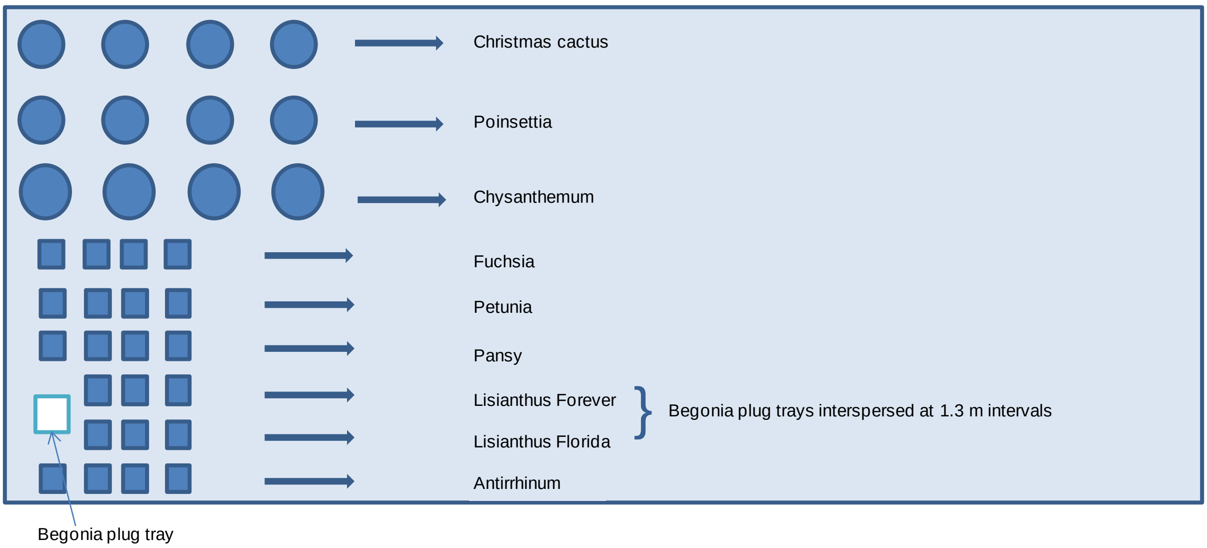


Figure 3. Layout plan for benches used in light gradient experiments

Recording plant response:

Response to treatments was recorded through regular visual checks on plants. Once flowering became apparent through the appearance of visual buds, formal inspections commenced for that species with records taken three times a week with date of first visible bud per plant and first open flower per plant recorded.

For some species, the appearance of buds and then flowers was not an appropriate measure of the effects of the LD treatments. In these cases, the following data were recorded:

Poinsettia: date of first bract / leaf reddening and first visible cyathia.

Chrysanthemum: date of first visible bud plus leaf number beneath the first visible bud to the node above the main stem.

Begonia: tuber formation was evaluated by destructive samples taken at the end of the experiment (10/02/10). A sample of 8 guarded plants from within each tray section were assessed for count of leaves greater than 0.5 cm, plant fresh weight (i.e. weight of leaves plus tubers with fine roots removed), tuber fresh weight, plant bulk dry weight, and tuber diameter.

Photographs in appendix I illustrate how the stages recorded were defined for each species.

Glasshouse environmental data:

Air temperature, RH, vent opening and pipe temperatures were collated from the Priva data storage system. Air temperature was also logged using independent sensors within the main glasshouse compartment and in each photoperiod cabinet. Set points were adjusted to ensure consistency of average achieved temperature in each glasshouse. Light sensors were also used to monitor the DE and NB treatments and achieved light intensities on the light gradient benches. Bulbs were checked and replaced as necessary on a weekly basis.

A photographic record of treatments was also kept.

Results

Given the layout of the experiment and the need to maintain a balanced design, two separate analysis of variance tests were used to compare the photoperiod cabinet data. One test compared all LD types (DE and NB with both T and CF lighting) at the 2.5 µmol/m^2/s level; and the other compared the three light levels, 1, 2.5 and 5 µmol/m^2/s, for the DE and NB treatments given with the CF lamp type only. This means there is no formal comparison between light levels delivered using T lamps. Standard errors of individual means are plotted on the bar charts representing these treatments which provides an indication of the variability of all data included.

Regression analyses were used to determine if light level influenced response within the light gradient experiments. Significance is expressed where probabilities resulting from analyses are at the <0.05 level.

Antirrhinum Red Bells – development of visible buds

Both tungsten NB and DE significantly ($P<0.05$) hastened the appearance of first visible buds compared with the SD treatment which developed buds after 56.4 days (figure 4). T was more effective as DE than NB and both 1 and 2.5 µmol/m^2/s T NB treatments produced similar results to each other.

Compact fluorescent lighting produced more variable effects. Overall the time to first visible bud was longer for CF treatments compared with T and whilst differences between NB and DE treatments appear to vary with intensity, the CF treatments were statistically no different to the SD treatment.

Clearly then delivering LD with CF lamps was ineffective for this variety. T lamps did hasten flowering and T was better as a DE than a NB treatment in this case.

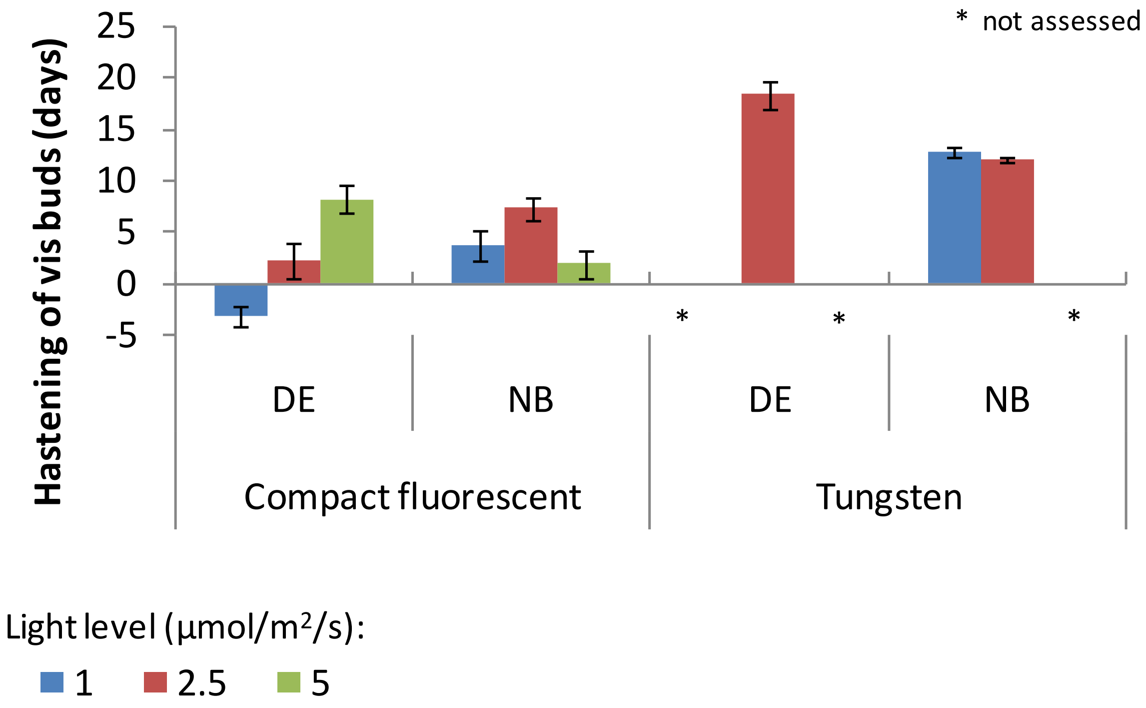


Figure 4. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level, on the time of bud appearance relative to that of the short day treatment. Negative numbers indicate where the lighting treatments delayed flower bud appearance. (SEM represented by error bars)

The data from the photoperiod cabinets is backed up by that from the light gradient experiments on benches (figure 5). That is, T NB generally hastened the development of first visible buds (with visible buds appearing 35 to 47 days from starting treatments) with no significant impact of T light level within the range tested. The T DE treatment, which was the most effective at hastening flowering in the cabinet experiments, was not represented in these light gradient experiments.

There was greater variation in the data for the two CF treatments with majority of plants developing visible buds 45 to 57 days from the start of treatments, but again, there was no significant correlation between CF light level for either the NB or DE treatments, suggesting that increasing light level of CF lamps up to 9.3 µmol/m^2/s would not be sufficient to promote flowering.

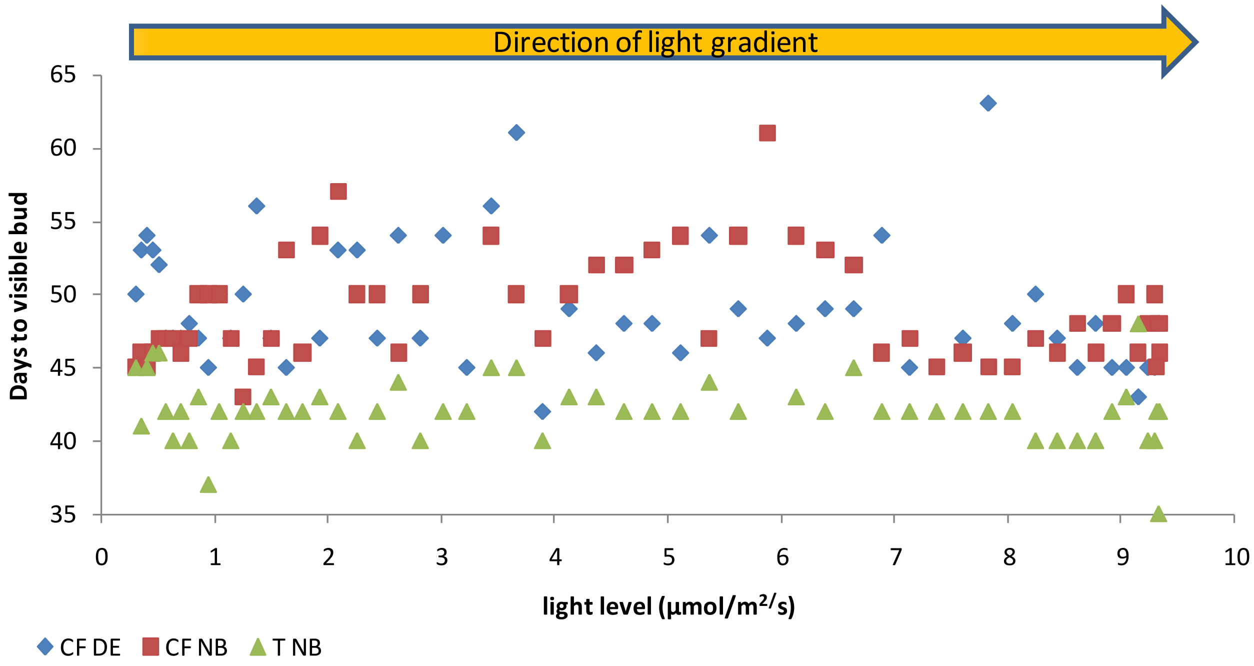


Figure 5. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time of bud appearance for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

Antirrhinum Red Bells – development of flowers

The influence of treatments on the time for buds to develop into flowers was also assessed (figure 6). Flowers developed from the first visible buds 26.5 days from the start of treatments when plants were in SDs. This time was significantly ($P<0.05$) reduced by 6-7 days, in T DE or NB treatments at 2.5 µmol/m^2/s with no difference between the two types of LD treatment in this case.

The CF LD treatments had no significant influence over the time taken for buds to develop into flowers compared with the SD control.

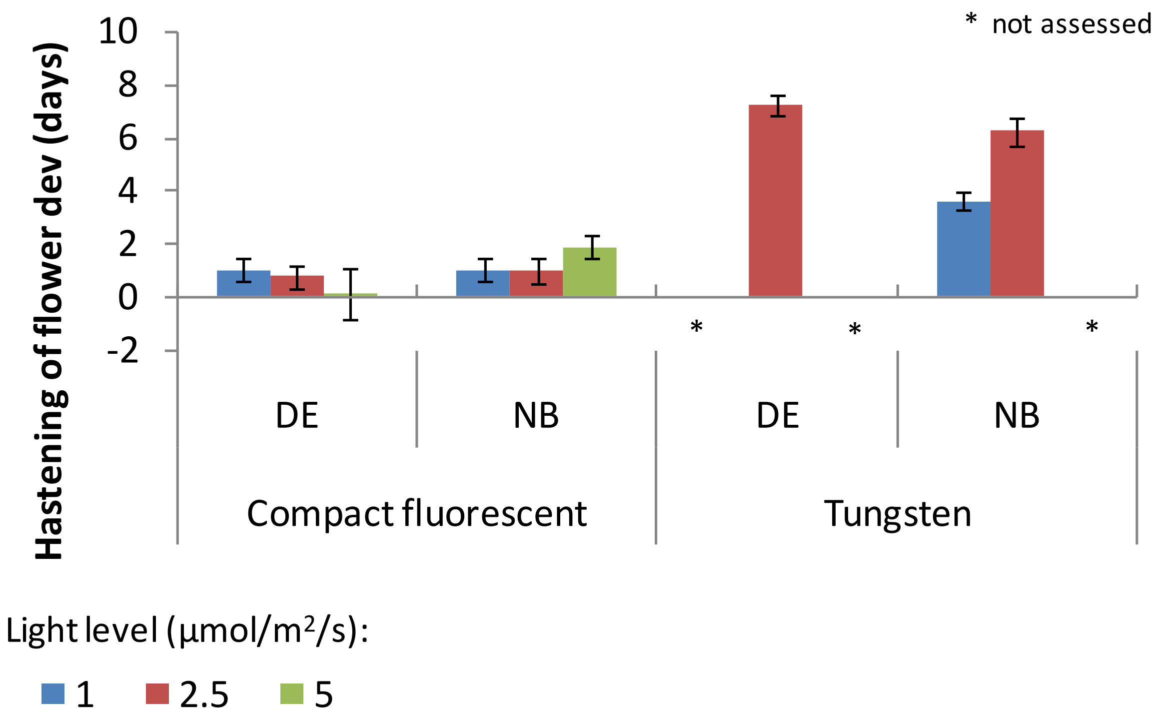


Figure 6. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time for flower development relative to that of the short day treatment. Negative numbers indicate where the lighting treatments delayed flower development. (SEM represented by error bars)

Data from the light gradient experiments (Figure 7) again support the photoperiod cabinet work described above. That is, visible buds developed into flowers soonest in the T NB treatment (after 18 to 21 days), compared with an average of 26.5 days for plants in SD cabinets. The extent of hastening of flower development was not significantly correlated with light level along the T NB light gradient.

As with time to first visible bud, plants grown in both the NB and DE CF gradients had similar times for flower development (i.e. ranging from 21 to 27 days) regardless of position in the light gradient with data generally variable along the length of the gradient.

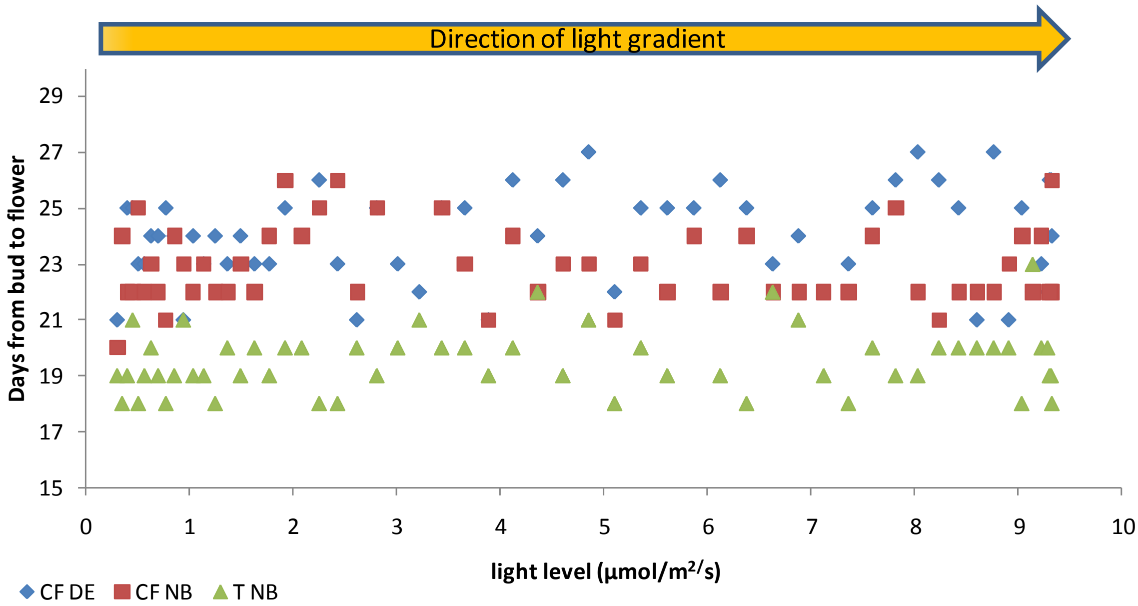


Figure 7. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time for flower development for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 µmol/m^2/s are presented in figure 8. That is, T lamps were the most effective at hastening flowering of Antirrhinum (Bells Red), with DE flowering slightly earlier than NB (after 57.3 and 64.6 days from the start of treatments respectively). The SD control treatment flowered on average 83.0 days from the start of treatments.

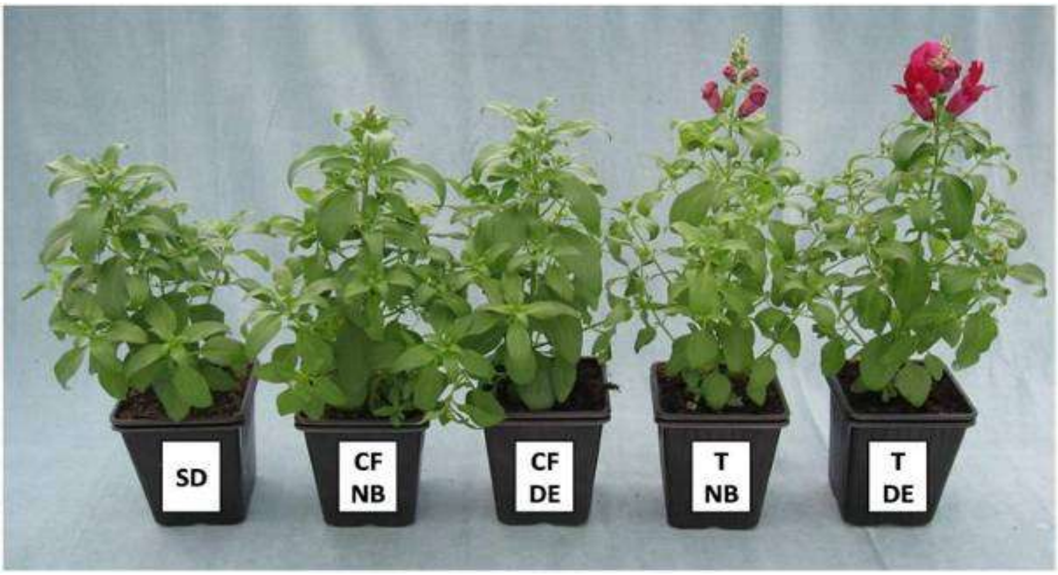


Figure 8. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 µmol/m^2/s on antirrhinum (Bells Red)

The main parameter of interest for the begonia plugs was tuber formation and hence evaluation of treatments focused on the size of tuber developed, and to put this in context, overall plant size was also measured. Assessments were made at a fixed time point (64 days after the start of treatments) by taking a destructive sample.

All LD treatments reduced the fresh weight of tubers by around 0.12 to 0.19g or an equivalent to 41-66% reduction of the fresh weight of tubers produced by the SD plants (at an average tuber fresh weight of 0.29g)(figure 9). Neither lamp type nor light level had a significant influence over tuber fresh weight.

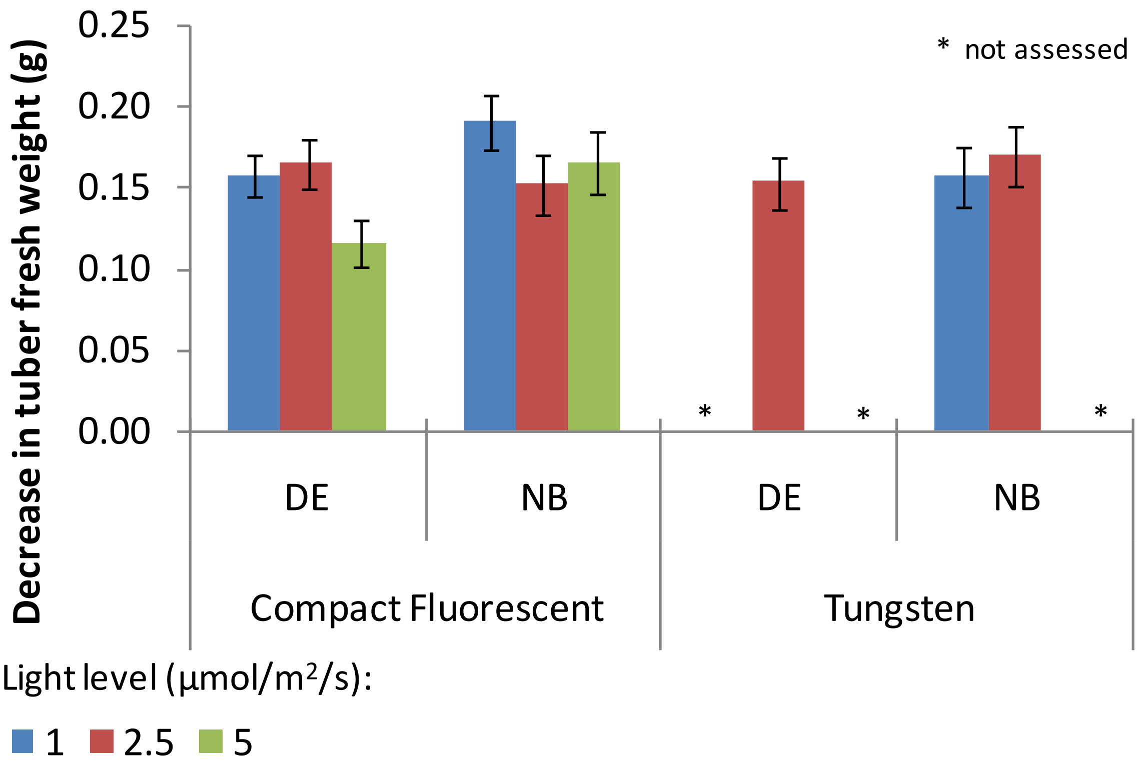


Figure 9. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on tuber fresh weight. Data is expressed as a decrease in weight compared with the SD (control) treatment. (SEM represented by error bars)

Tuber fresh weights from plants grown within the light gradients were comparable with those from the LD treatments in the photoperiod cabinet experiments above (i.e. ranging between 0.10 and 0.15 g per plant). There were too few points to conduct a formal regression analysis on these data, however, if effectiveness of treatment had decreased at lower light levels, an increase in tuber fresh weight would be expected at the lower end of the gradient which is not reflected in the data collected (figure 10).

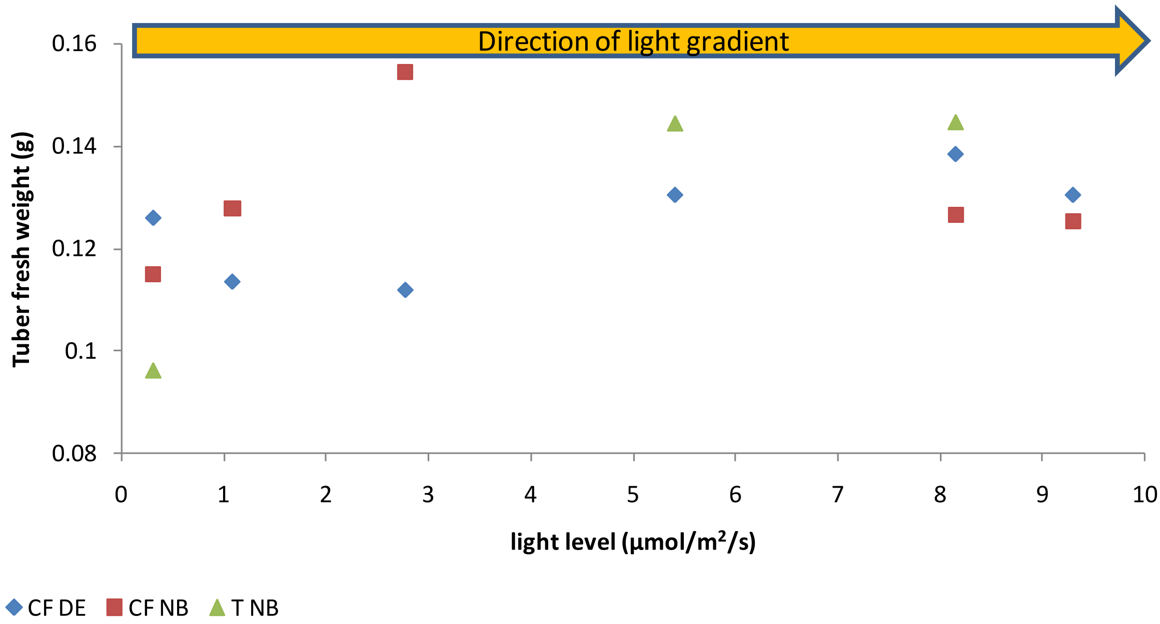


Figure 10. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on tuber fresh weight for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

Treatments had a comparable impact on tuber diameter (figure 11). That is all LD treatments reduced the size of tuber diameter by 1.9 to 2.7 mm compared with the SD plants which had an average tuber diameter of 9.2mm. There were no significant differences between lamp types or LD types in terms of the extent of the reduction of tuber diameter.

Both lamp types and LD types were therefore equally effective in preventing tuber formation.

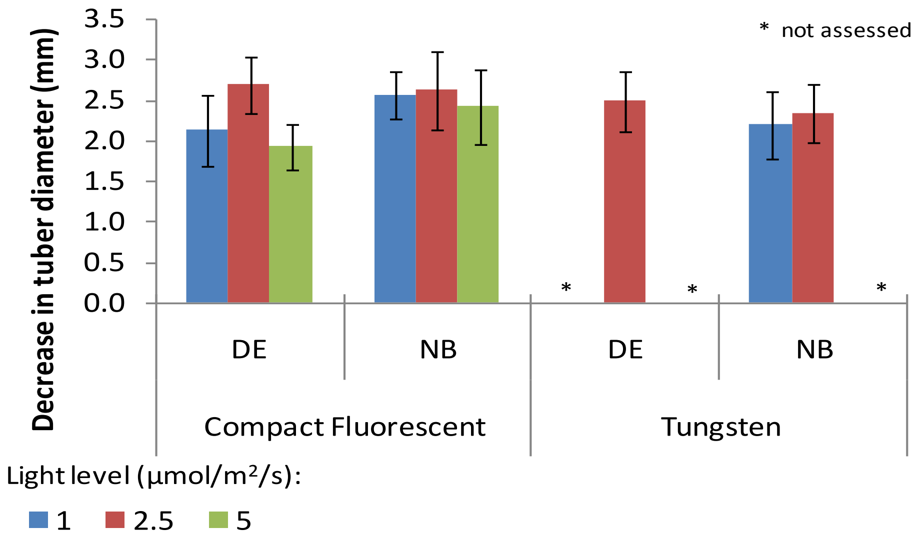


Figure 11. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on tuber diameter. Data is expressed as a difference from the SD (control) treatment. (SEM represented by error bars)

Tuber diameters from plants grown within the light gradients were comparable with those from the LD treatments in the photoperiod cabinet experiments (i.e. ranging between 5.8 and 7.4 mm). There were too few points to conduct a formal regression analysis on these data; however, if effectiveness of treatment had decreased at lower light levels, an increase in tuber diameter would be expected at the lower end of the gradient which is not reflected in the data collected (figure 12).

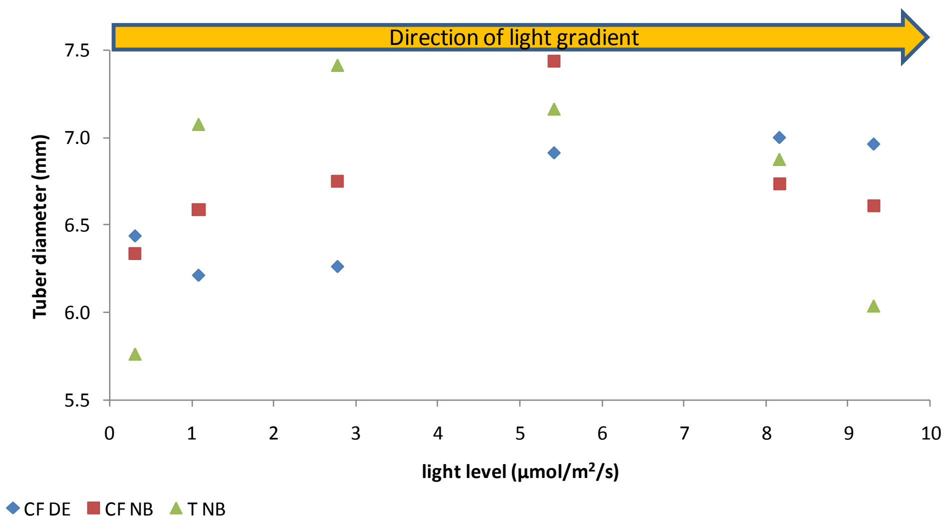


Figure 12. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on tuber diameter for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

In contrast to tuber formation, LD treatments increased overall plant size by an average of 0.4 to 1.0g per plant over the 0.56 g average total fresh weight of plants grown in SD (figure 13). The total fresh weight data was variable between LD treated plants and not significantly influenced by either type of LD treatment or light level used.

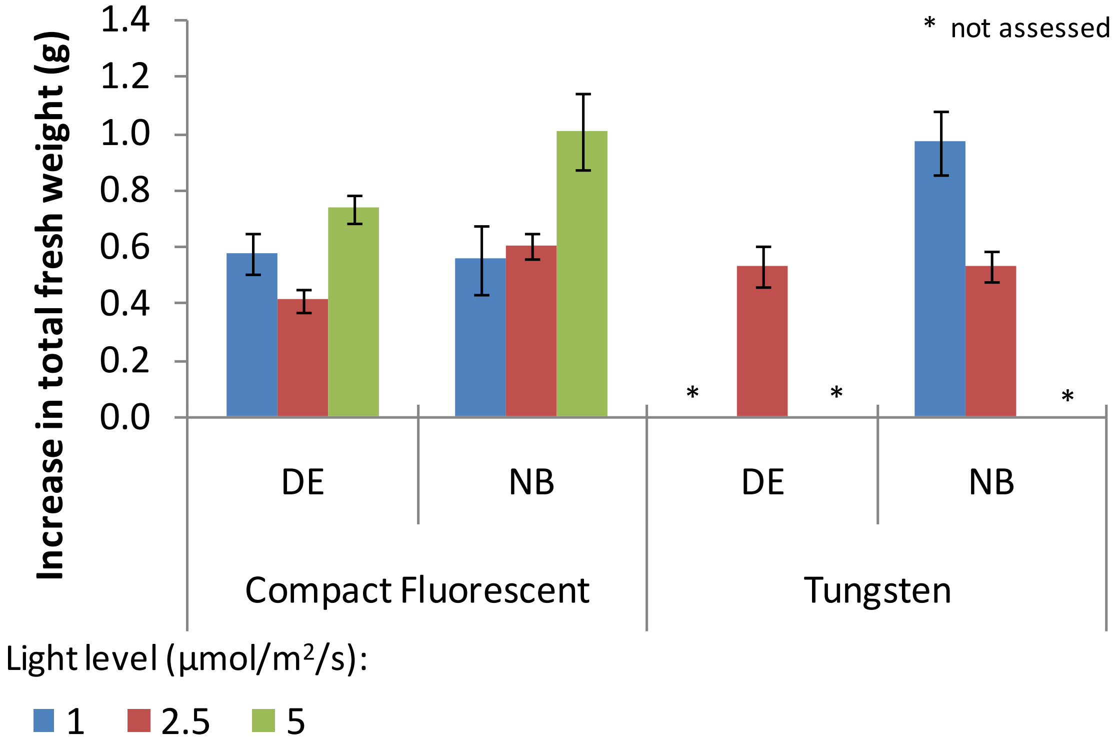


Figure 13. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on total plant (i.e. shoot plus tuber) fresh weight. Data is expressed as a difference from the SD (control) treatment. (SEM represented by error bars)

All plants along the three light gradients had total fresh weight within the range 0.9 to 1.3 g which is comparable with the plants in the photoperiod cabinet experiments. There is no evidence of light gradient influencing this parameter from the limited data collected (figure 14).

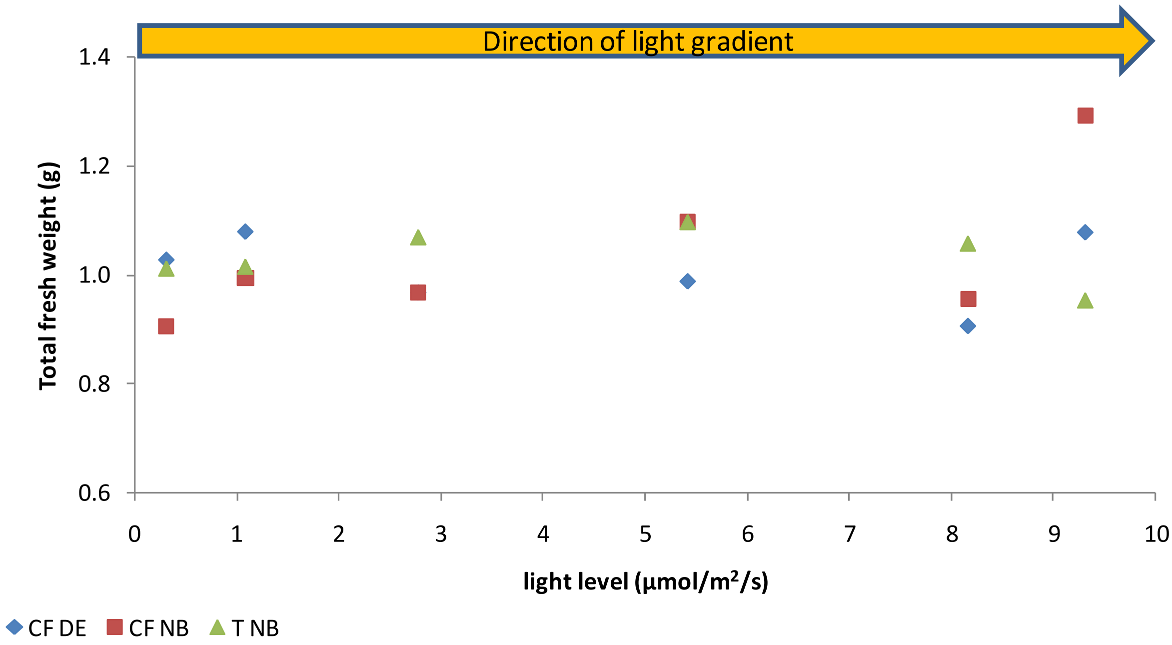


Figure 14. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on total plant fresh weight for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 µmol/m^2/s are presented in figure 15. That is, both lamp types and both types of LD promoted growth of shoots which increased total plant weight whilst plants in SD developed tubers at the expense of shoot growth.

Figure 15. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 µmol/m^2/s on begonia (Illumination Rose)

Christmas cactus Olga – development of visible buds

All LD treatments significantly (P<0.05) delayed the appearance of visible buds of this SD species (which developed visible buds in 22 days under SD conditions); producing negative hastening of flowering data (figure 16). The T DE treatment at 2.5 µmol/m^2/s had the greatest impact on development of visible buds, resulting in an average delay of 17 days with T NB delaying the appearance of visible buds by an average of 6 to 9 days.

LD treatments using CF lamps resulted in less delay in the appearance of visible buds with DE being more effective (9-11 day delay) than NB (4-6 day delay).

Light level was not significant within the range and treatments tested in this experiment.

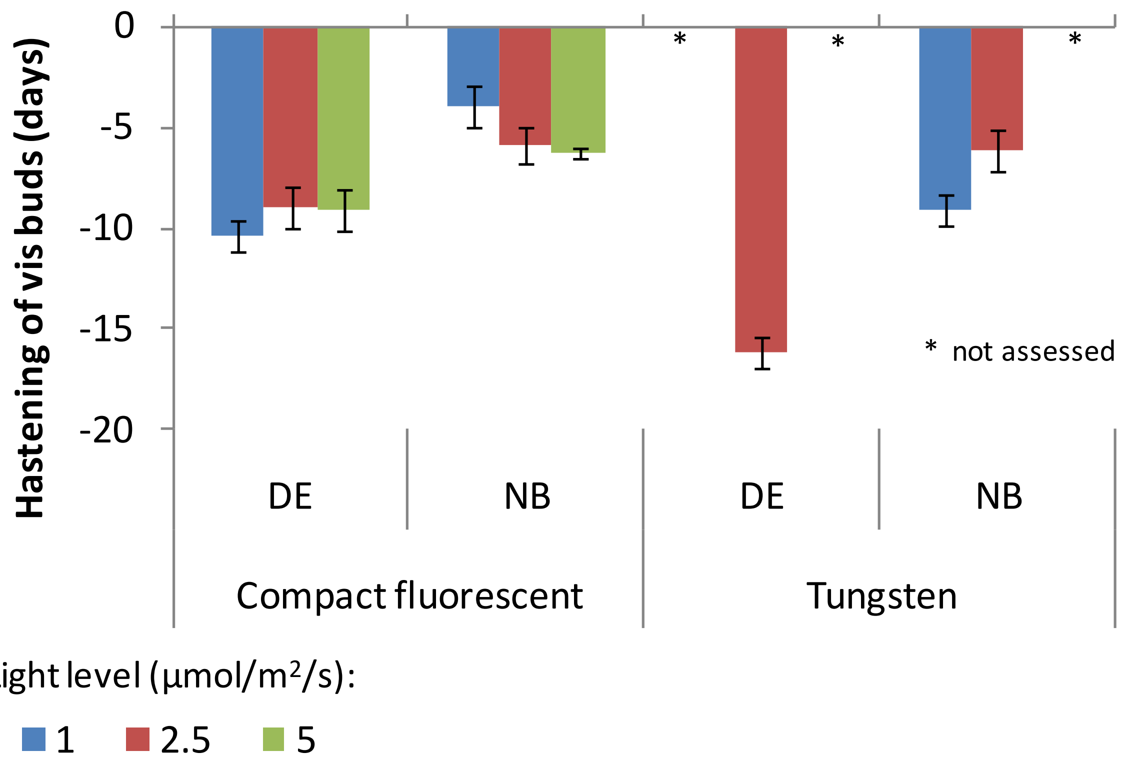


Figure 16. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time of bud appearance relative to that of the short day treatment. Negative numbers indicate where the lighting treatments delayed flower bud appearance. (SEM represented by error bars)

All LD treatments produced similar results in the light gradient experiments with time to visible bud ranging between 25 and 35 days from the start of treatments, which represents a delay in flowering of between 3 and 13 days, along most of the light gradient (figure 17). The effectiveness of the LD treatment was significantly correlated with light level due to a reduction in effectiveness at the lower end of the light gradients for all LD treatments (i.e. <1 μmol/m^2/s) with time to visible buds at 22 days which was equivalent to that produced by the SD treatments in the photoperiod cabinet experiments. The most effective LD treatment for this species from the photoperiod cabinet experiments (i.e. T DE) was not represented in the light gradient experiments.

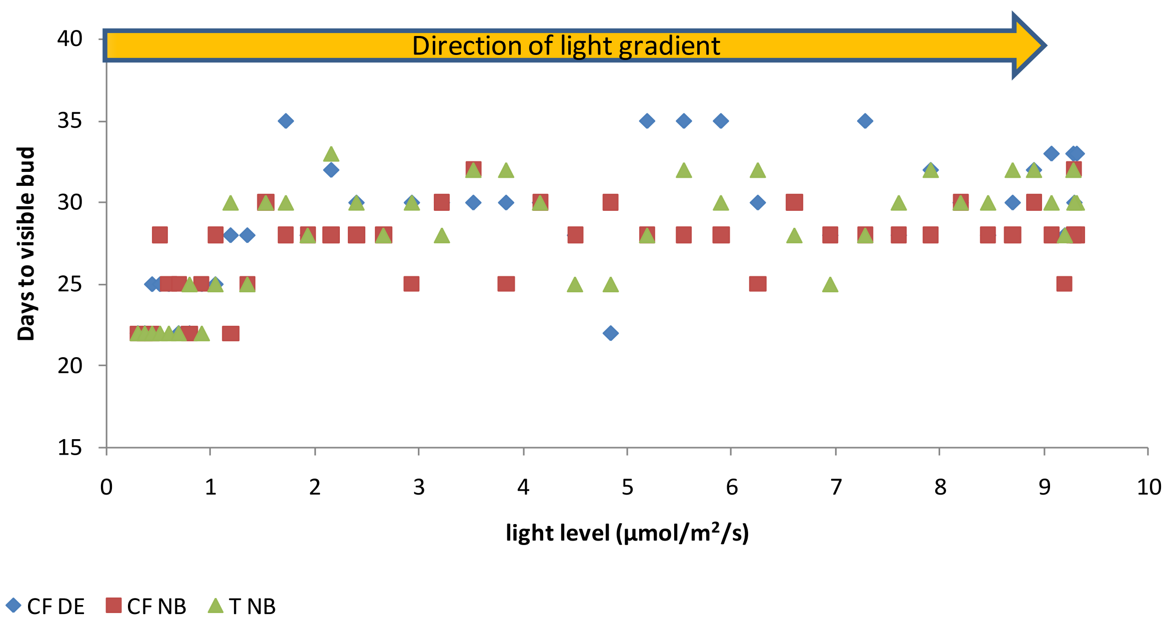


Figure 17. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time of bud appearance for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 μmol/m^2/s

Christmas cactus Olga – development of flowers

None of the LD treatments had a significant influence over the time taken for visible buds to develop into flowers compared with the SD control where buds developed into flowers in an average of 50 days (figure 18).

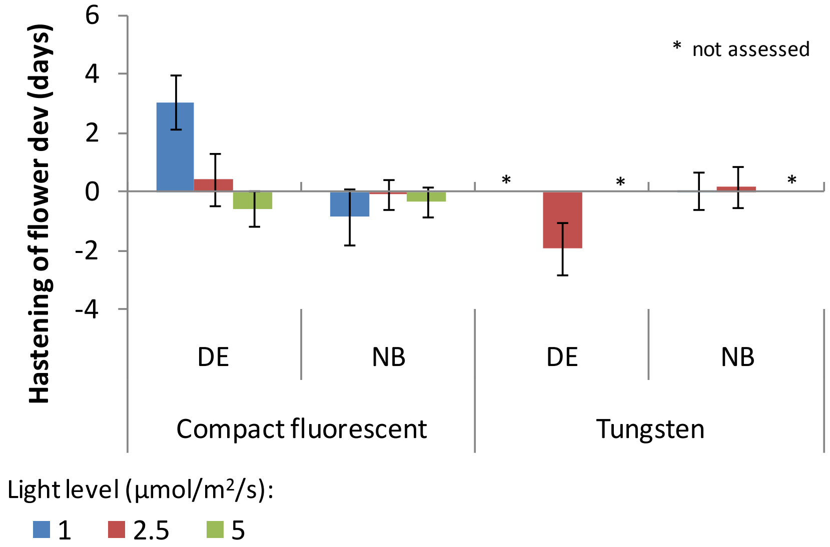


Figure 18. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time for flower development relative to that of the short day treatment. Negative numbers indicate where the lighting treatments delayed flower development. (SEM represented by error bars)

Flowers took an average of 52 days to develop from visible buds in plants exposed to LD along the light gradient benches compared with 50 days for the SD control. Hence whilst there is a slight decrease in time for flower development at the lower end (<0.1 µmol/m^2/s) of the gradient with regression analysis suggesting a significant correlation, the actual difference may have little commercial significance.

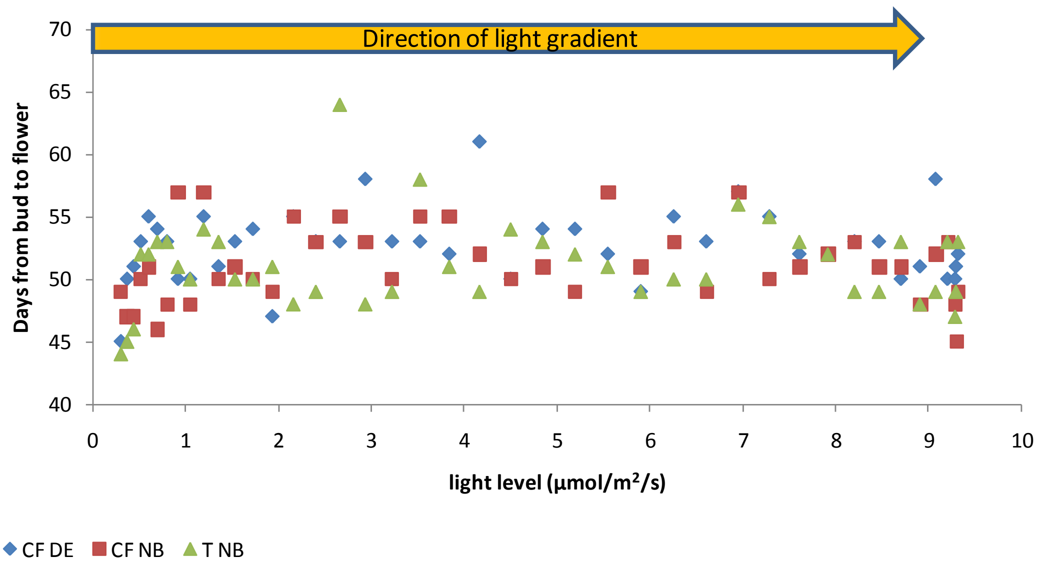


Figure 19. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time for flower development for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 μmol/m^2/s are presented in figure 20. That is, T DE was the most effective at delaying flowering of Christmas cactus (Olga), with some delay resulting from T NB as well as CF NB and CF DE. The SD control treatment flowered on average 77 days from the start of treatments. N.B. Plants used in these trials were partly grown and had already received T DE extension lighting on the commercial producer site before starting treatments; hence the data here may not show full extent of differences between lamp types and LD type.

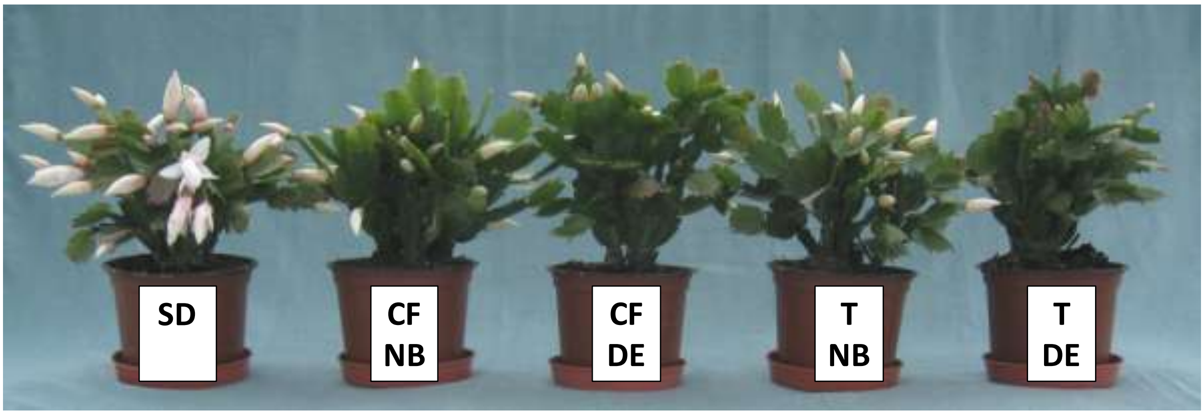


Figure 20. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 μmol/m^2/s on Christmas cactus (Olga)

Chrysanthemum Tampico – development of visible buds

All LD treatments delayed flowering of this SD species producing negative hastening of flowering data (figure 21). In fact whilst a visible bud was eventually produced on plants in all of the LD treatments, these represented autonomous flowering on side shoots with 17-20 leaves below the bud. There were no significant differences relating to lamp type, type of LD treatment or light level in these experiments. Control plants grown in SDs flowered normally, with visible buds first appearing 24 days after the start of treatments.

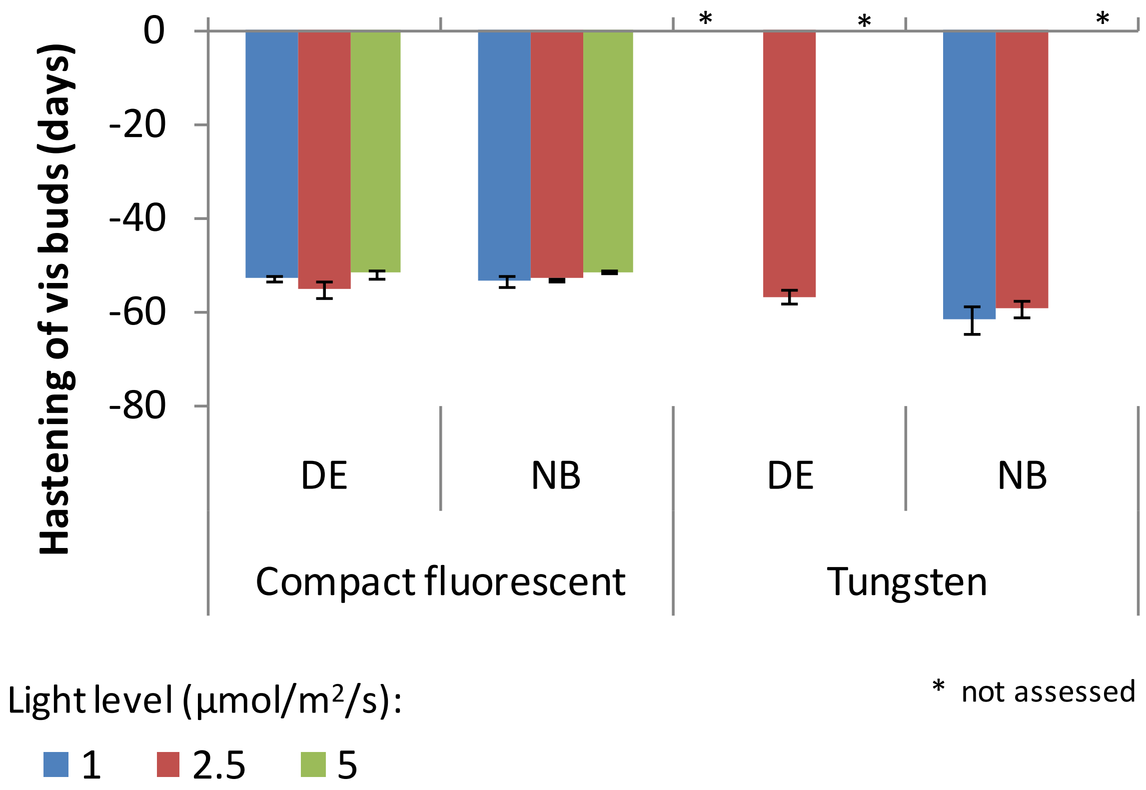


Figure 21. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time of bud appearance relative to that of the short day treatment. Negative numbers indicate where the lighting treatments delayed flower bud appearance. (SEM represented by error bars)

As indicated by the photoperiod cabinet experiments above, the T NB, CF DE and CF NB treatments delayed flowering at all light levels along the gradients created. Visible buds appeared after 76-78 days even at the lowest light level on the gradient (0.3 µmol/m^2/s) for the different lamp and LD types. As in the photoperiod cabinet experiments, these buds were the result of autonomous flowering. Results appeared more variable for plants grown with the CF NB treatment than the others tested, but overall light level did not significantly influence time to the appearance of the first visible bud.

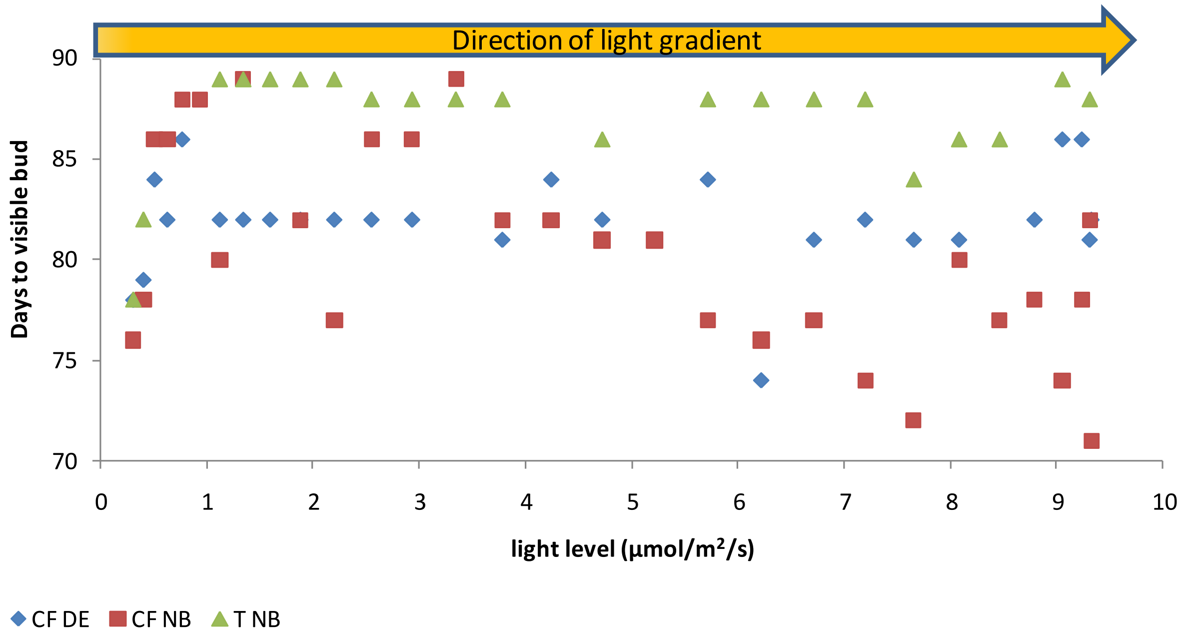


Figure 22. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for the appearance of visible buds for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

As few of the LD treated plants produced open flowers before the end of the experiment, the time for flowers to develop was not estimated. The time to visible bud data was however reinforced by leaf counts taken at the end of the experiment (after 84 days in treatments). As with the visible bud data it is clear that all LD treatments delayed flowering since all plants had a significant increase in leaf number on the side shoot below the first bud (figure 23) compared with plants in SD treatments (at 7 leaves). There were 9 to 13 extra leaves produced on side shoots as a result of LD treatments compared with the SD control and neither lamp type nor LD type significantly influenced these data.

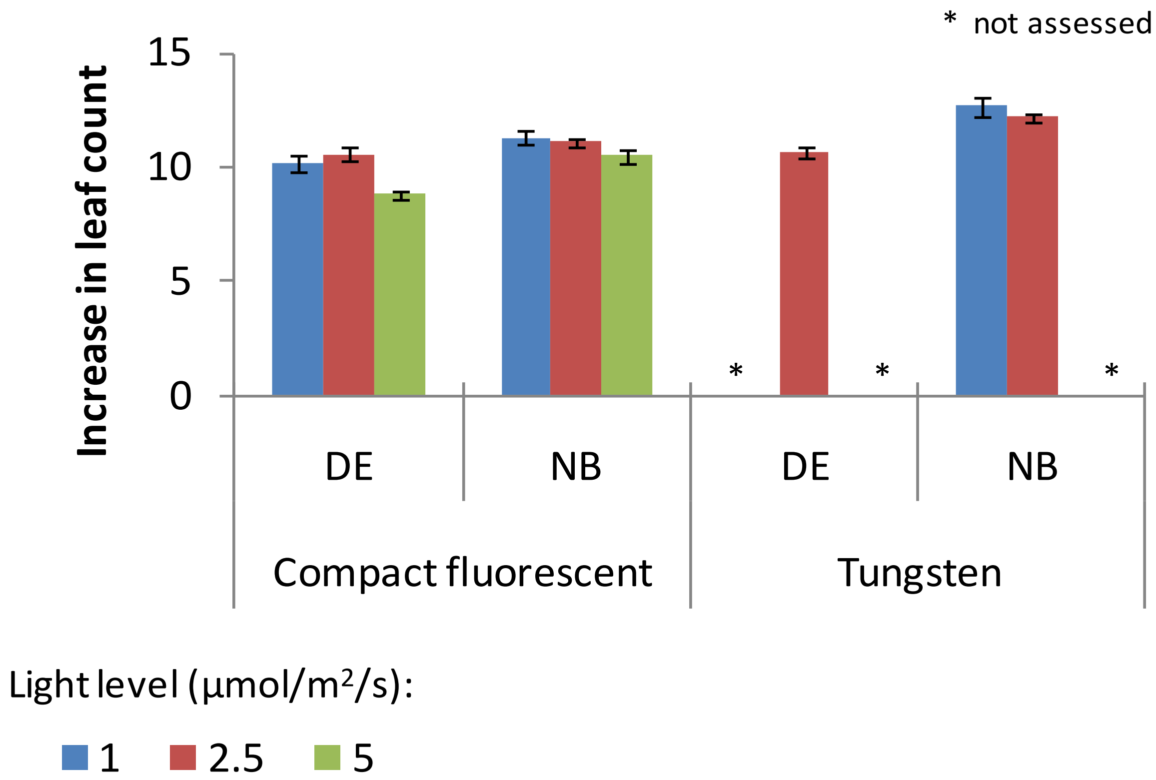


Figure 23. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on increase in leaf count compared with plants grown in SD (with higher leaf number indicating a delay in flowering). (SEM represented by error bars)

Plants grown in light gradients further confirm the results for Chrysanthemum grown in the LD treatments (figure 24). That is leaf number below the bud was similar along the light gradient created (ranging between 17 and 21 leaves below the bud on the most advanced side shoot from each pot) down to the lowest level of 0.3 µmol/m^2/s and all treatments produced a comparable response.

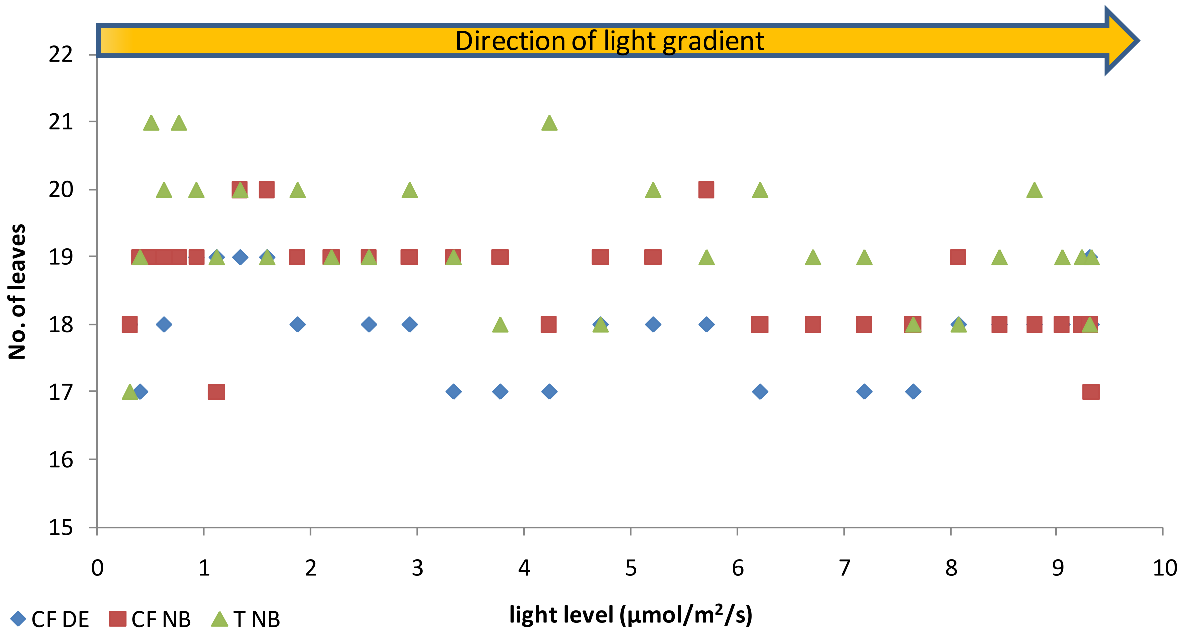


Figure 24. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the number of leaves below the bud of the most advanced side shoots per pot for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 µmol/m^2/s are presented in figure 25. That is, only SD plants of chrysanthemum Tampico flowered normally (budding 24 days after the start of treatments) and all LD treatments assessed were effective in delaying flowering.

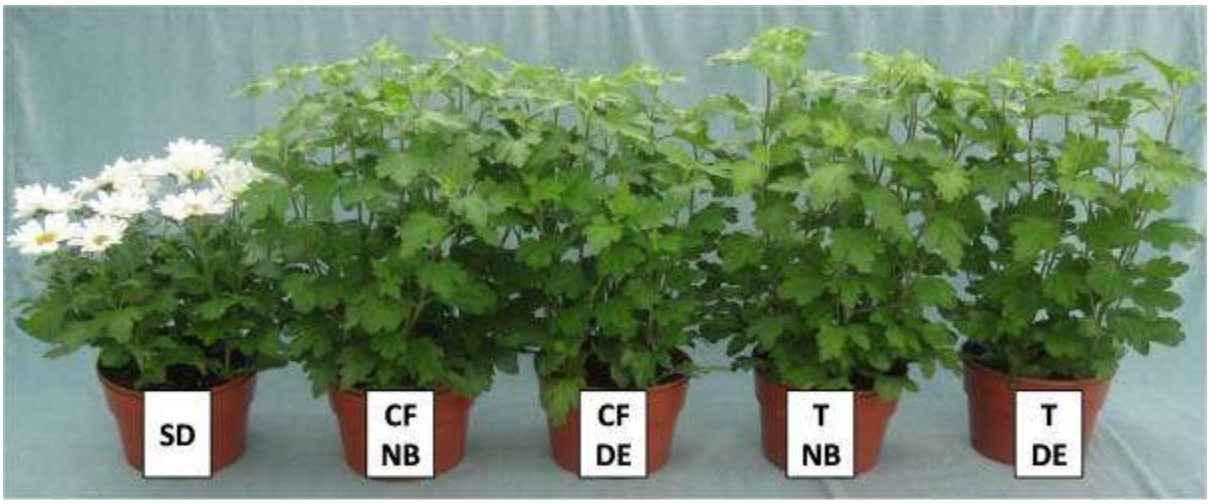


Figure 25. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 µmol/m^2/s on chrysanthemum (Tampico)

Fuchsia Patio Princess – development of visible buds

None of the SD treatments had developed buds by the end of the experiment and hence assumed flowering date for this treatment has been taken as 193 days (i.e. days to end of the experiment). This means that data for the LD treatments can be compared on an equivalent basis to the other species covered in this report.

All LD treatments hastened the development of visible buds of this LD species compared with the SD control (figure 26). Overall the LD treatments produced visible buds at least 156-159 days sooner than the SD treatment which had still to develop buds 193 days after the start of treatments (that is, plants in LDs developed buds after 34 to 37 days from the start of treatments). All LD treatments were equally effective in promoting flowering with no significant differences relating to lamp type, LD type or light level.

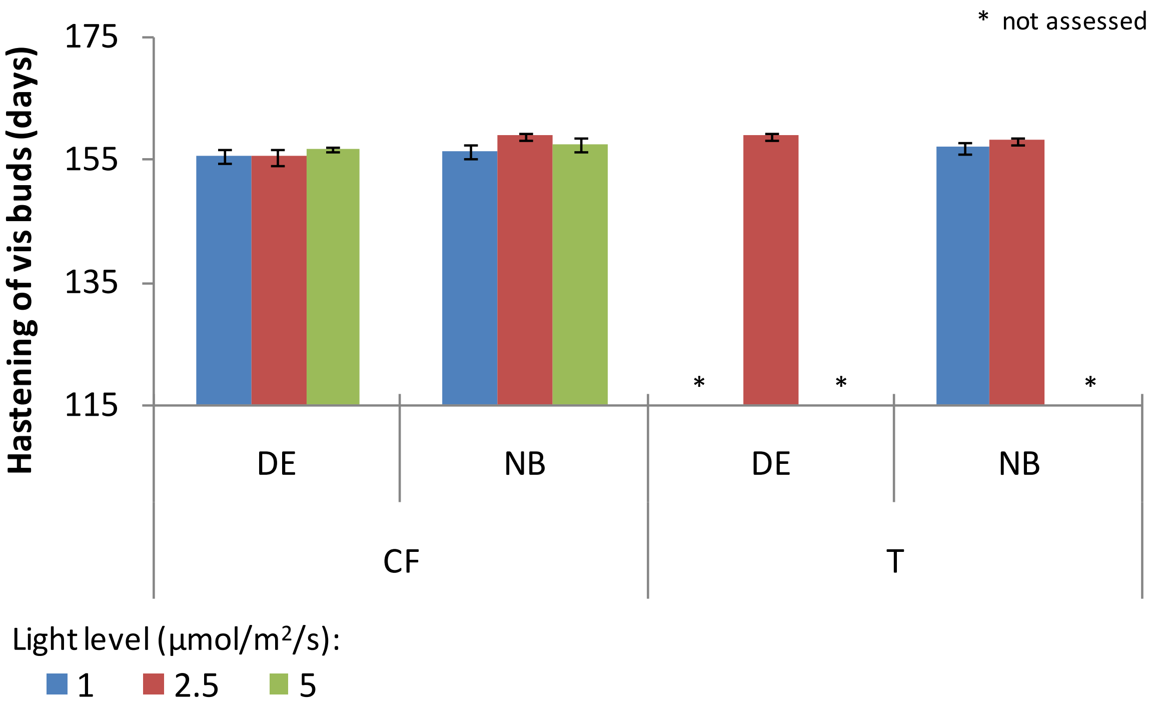


Figure 26. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time of bud appearance relative to that of the short day treatment (where SD plants had still not developed buds 193 after the start of treatments). Negative numbers indicate where the lighting treatments delayed flower bud appearance. (SEM represented by error bars)

All plants in the three light gradient experiments developed visible buds at a similar time (figure 27) with light level having no significant influence within the 0.3 to 9.3 µmol/m^2/s range assessed.

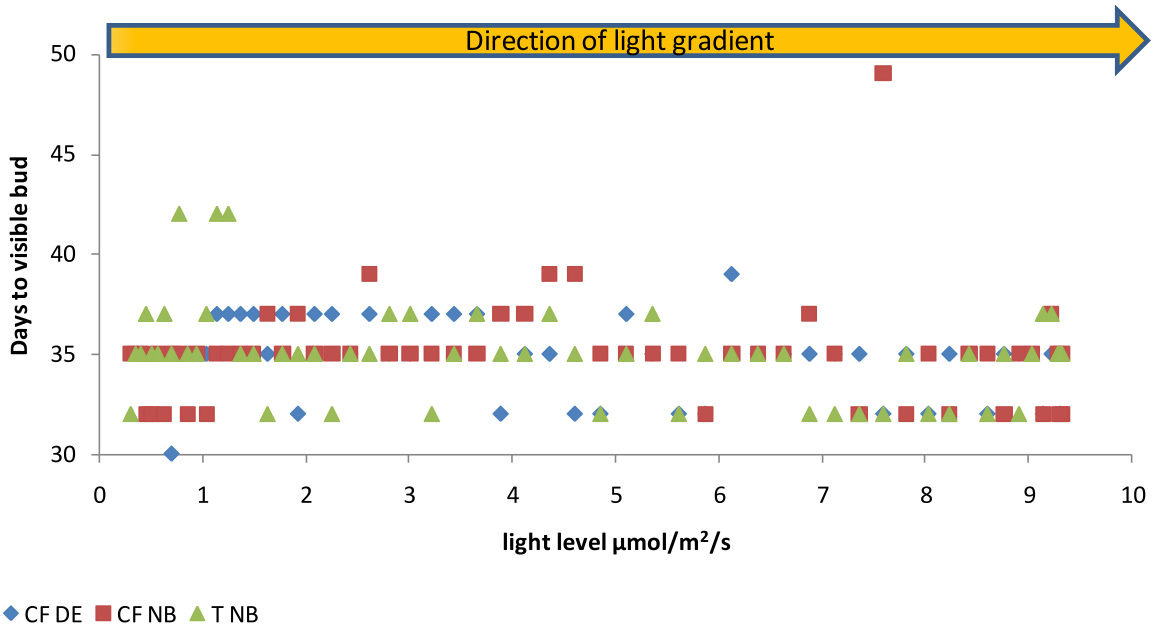


Figure 27. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for the appearance of visible buds for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

Fuchsia Patio Princess – development of flowers

None of the SD treatments had developed flowers by the end of the experiment and hence data for the LD treatments are compared rather than hastening of time to flowering as discussed elsewhere in this report.

LD treatments flowered between 68 and 78 days from the start of treatments with flower development therefore taking around 37 days from the development of visible buds (figure 28). As with the initial development of buds discussed above, all LD treatments hastened flower development compared with the SD control (still to develop open flowers after 193 days) and neither lamp type, nor LD type nor light level influenced this parameter.

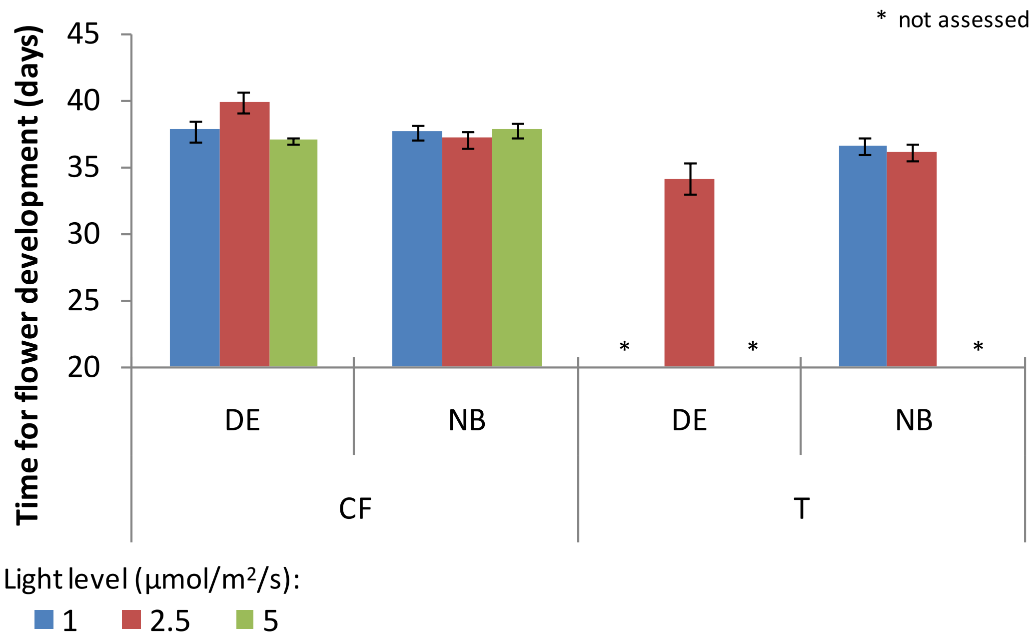


Figure 28. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time to the development of open flowers. (SEM represented by error bars)

All LD treatments were equally effective at promoting flowering along the light gradients set up (figure 29) with no significant correlations between light level and days from bud to flower.

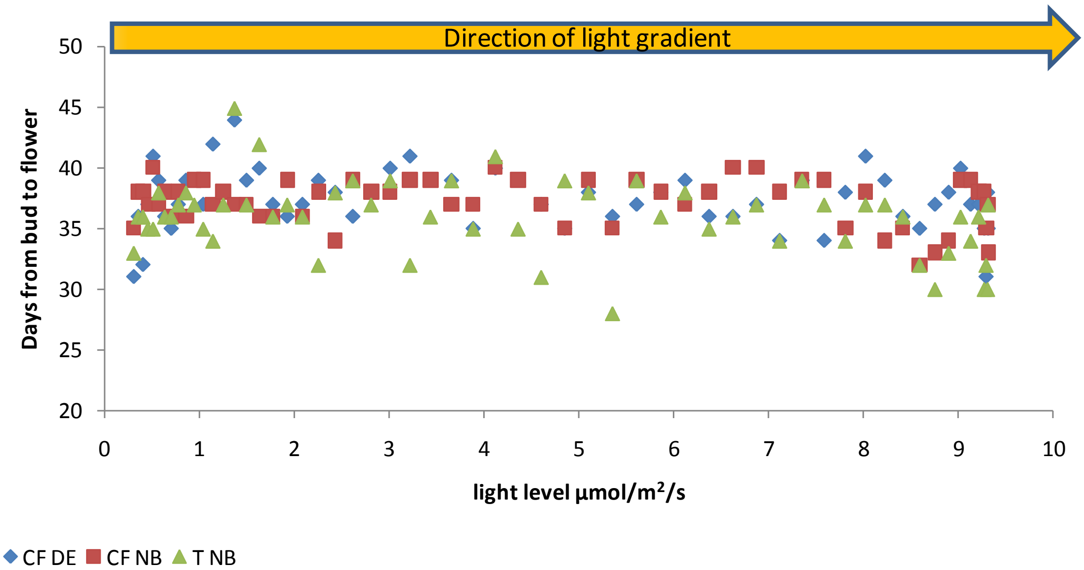


Figure 29. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for the appearance of flowers for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 µmol/m^2/s is presented in figure 30. That is, SD prevented flowering whilst all LD treatments assessed were effective in promoting flowering.

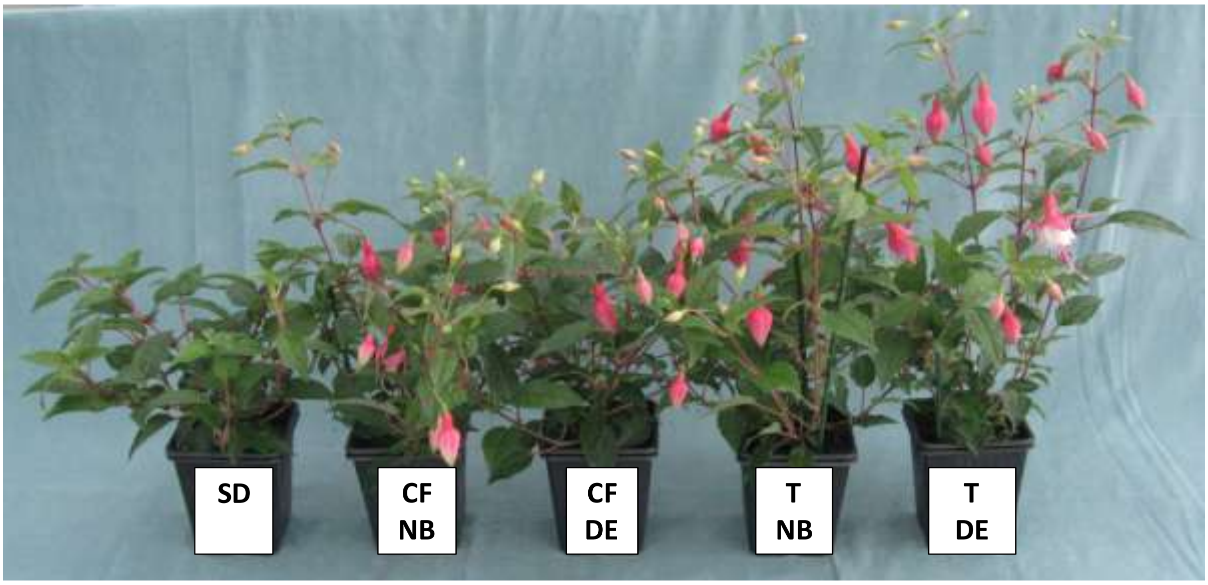


Figure 30. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 µmol/m^2/s on fuchsia (Patio Princess)

Lisianthus

Two different series of Lisianthus were included in the experiment to represent the earlier season Forever types and the later season Florida types.

Lisianthus Forever Blue – development of visible buds

Plants grown in SDs developed visible buds 159 days after the start of treatments. LD lighting with T significantly decreased time to first visible bud by 36 to 42 days, and DE lighting was significantly more effective than NB lighting when given with T lamps (figure 31). CF lighting was significantly less effective than T with the CF DE giving no significant hastening of the development of visible buds compared with SD. Giving CF lighting as a NB was more successful with buds appearing 9-19 days sooner than the SD treatment. It is not clear why the 2.5 µmol/m^2/s treatment appeared more effective than the higher and lower level CF NB treatments since the light gradient experiments below suggest no correlation between light level and time to first visible bud.

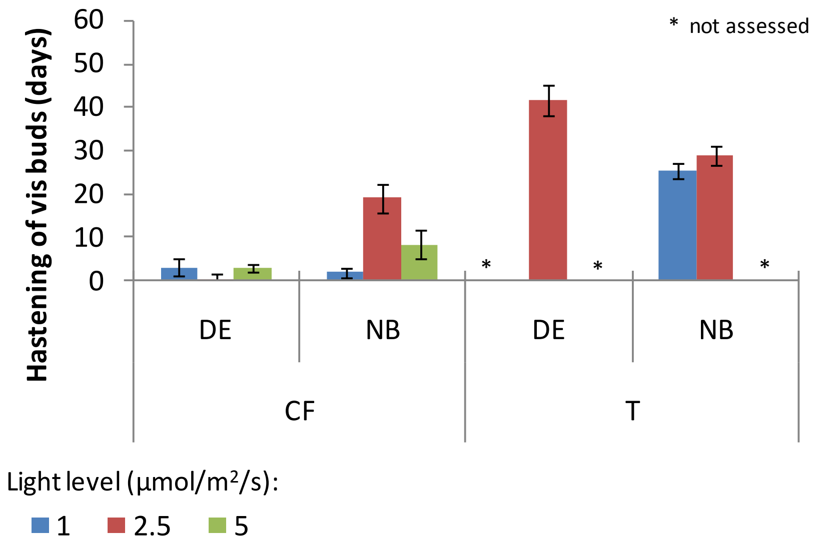


Figure 31. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time of bud appearance relative to that of the short day treatment. (SEM represented by error bars)

Plants developed visible buds at a similar time along the light gradients with no significant correlation between time to develop visible buds and light level (figure 32). The T NB treatment again consistently resulted in the shortest time to the development of visible buds compared with the two CF treatments. CF NB generally developed visible buds sooner than CF DE.

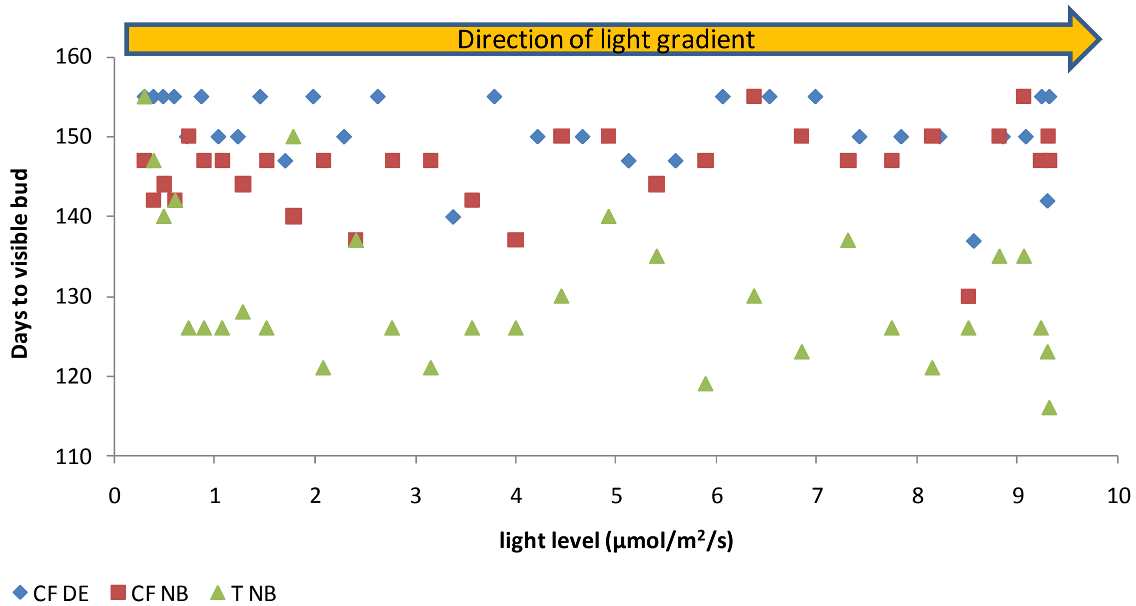


Figure 32. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for the appearance of visible buds for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

Lisianthus Forever Blue – development of flowers

There was insufficient flower development by the end of the experiment for the effects of the LD treatments to be assessed relative to the SD treatment within the photoperiod cabinet experiments. Limited data are available for the light gradient treatments (figure 33), where for T NB, buds developed into open flowers after 41 to 53 days and that light level within the range tested did not influence the timing of this process. Few of the CF treatments had developed open flowers and hence have less data on this graph. Flower development time for the CF DE treatment which has points along the length of the light gradient also did not appear to be affected by light level within the range tested.

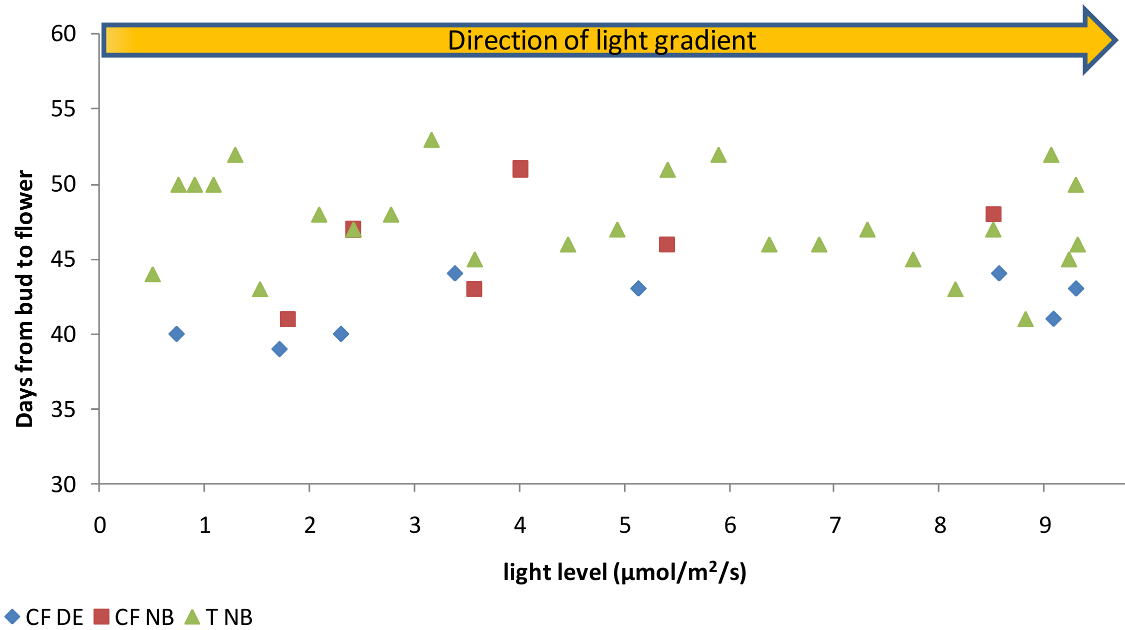


Figure 33. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for buds to develop into open flowers for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 µmol/m^2/s is presented in figure 34. T DE clearly resulted in the earliest flowering, followed by T NB. CF NB hastened flowering compared with SD but was less effective than T and CF DE did not hasten flowering.

Figure 34. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 µmol/m^2/s on lisianthus (Forever Blue)

Lisianthus Florida Silver – development of visible buds

Lisianthus Florida grown in SDs produced visible buds after an average of 178 days; around 18 days longer than that for lisianthus Forever summarised above. As with Forever, the time for Florida to develop visible buds was significantly shorter when plants were given LD treatment with T lamps; and development of visible buds was also significantly earlier with T DE (55 days sooner than the SD treatment) than with T NB (26-39 sooner than SD)(figure 35). CF also significantly hastened the development of visible buds, although less effectively than the T treatments. NB was the most effective CF treatment, reducing time to visible buds by 12-19 days. CF DE hastened the development of visible buds the least (9-12 days) which, given the variability in data, may not be commercially relevant. The light levels tested had no significant influence over the hastening of visible bud development.

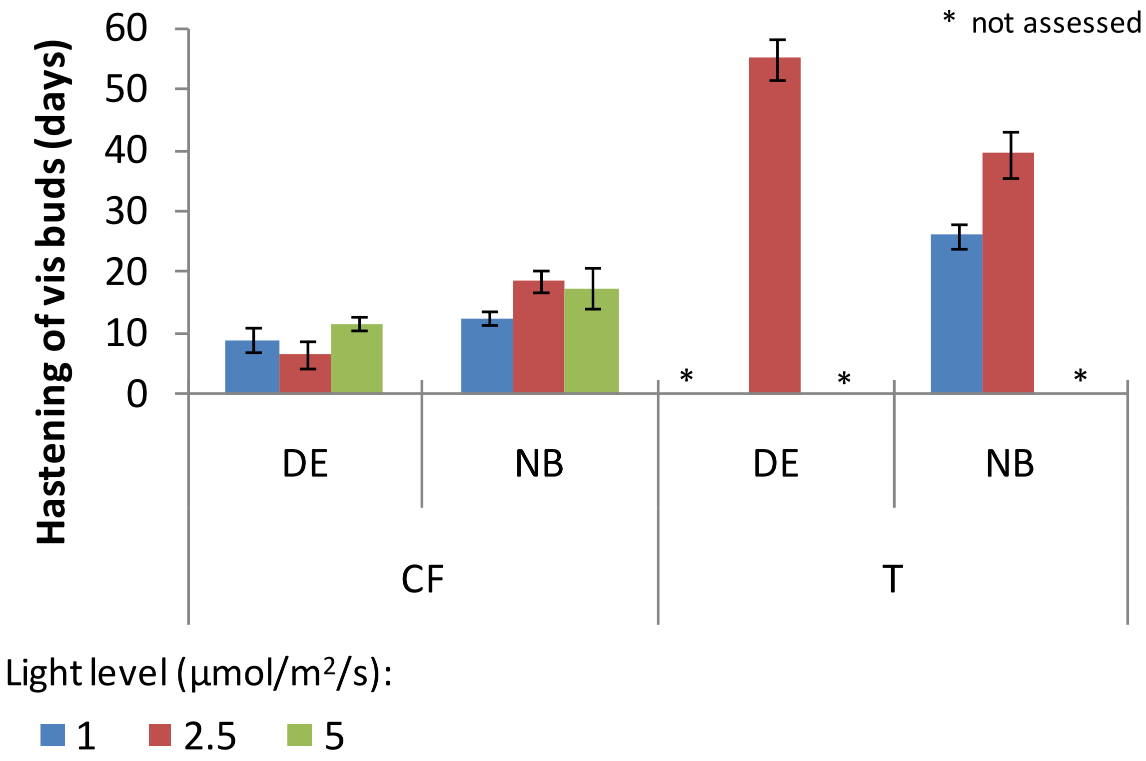


Figure 35. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time of bud appearance relative to that of the short day treatment. (SEM represented by error bars)

There was no significant correlation between time to develop first visible bud and position along the light gradient for lisianthus Florida which supports the results of the photoperiod cabinet experiment (figure 36). T NB was consistently more effective at hastening this measure of flowering (with time to first visible bud around 126 to 160 days) compared with the two CF treatments (which produced visible buds 142 to 168 days after the start of treatments). There is little separation between the two CF treatments but overall the CF NB treatment resulted in shorter times to visible bud development than the CF DE treatment along the gradient.

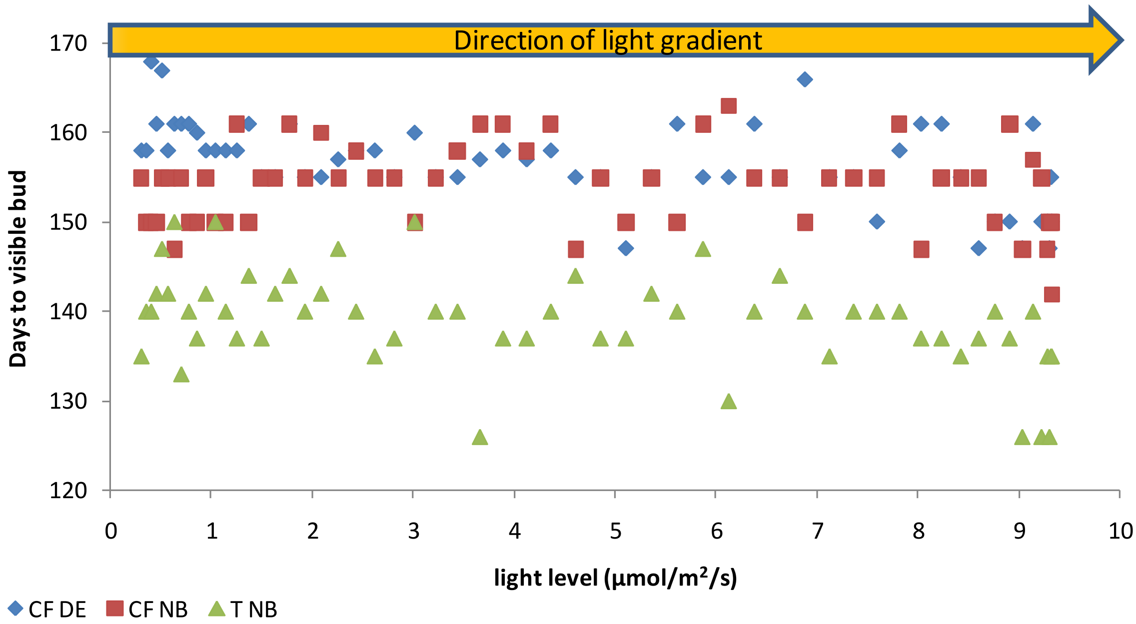


Figure 36. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for the appearance of visible buds for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

Lisianthus Florida Silver – development of flowers

There was insufficient flower development by the end of the experiment for the effects of the LD treatments to be assessed relative to the SD treatment from the photoperiod cabinet experiments. Limited data are available for the light gradient treatments (figure 37), where buds developed into open flowers between 42 and 54 days within the T NB gradient and that light level within the range tested did not influence the timing of this process. There are too few data from CF treatments to evaluate response to position on the gradient.

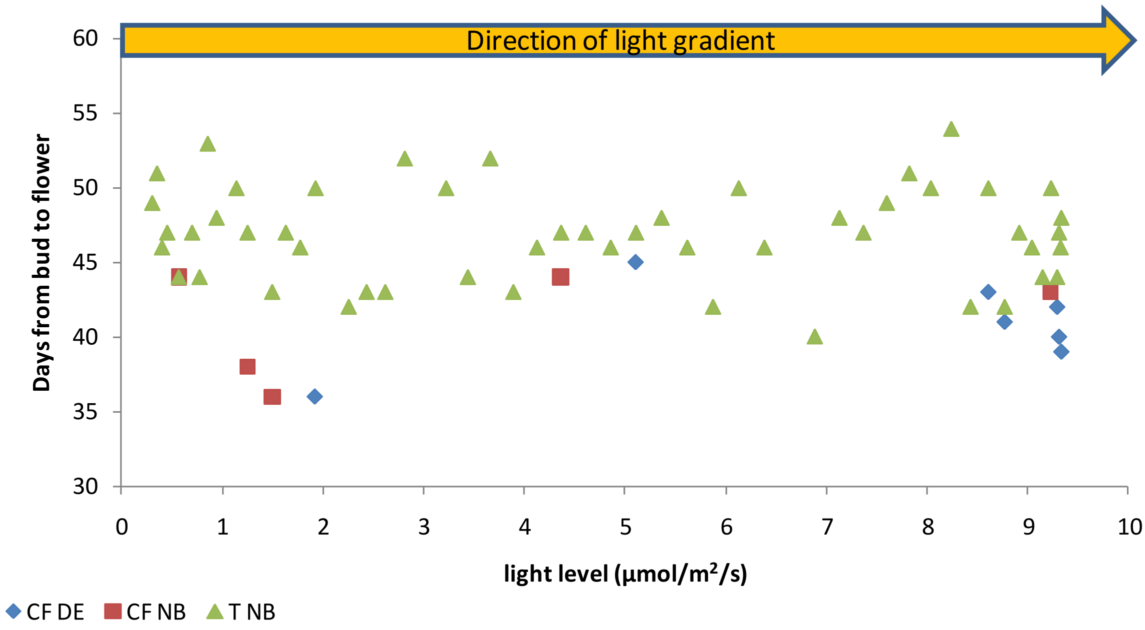


Figure 37. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for buds to develop into flowers for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 µmol/m^2/s are presented in figure 38. T DE clearly resulted in the earliest flowering, followed by T NB. CF NB hastened flowering compared with SD but was less effective than T and CF DE had little impact.

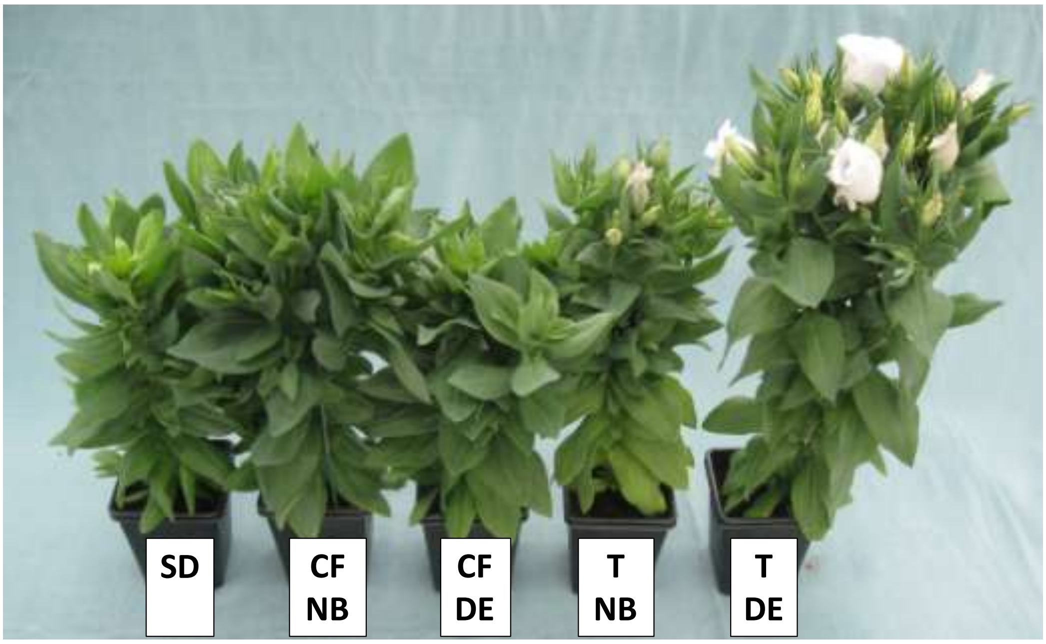


Figure 38. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 µmol/m^2/s on lisianthus (Florida)

Pansy Majestic Giant Purple – development of visible buds

Visible buds appeared significantly earlier (by 7-9 days) when plants were exposed to T as DE or NB compared with SD in photoperiod cabinet experiments, with both the 1 and 2.5 μmol/m^2/s treatments being effective (figure 39). In contrast, LD given with CF as either NB or DE were not significantly different to the SD control (which developed visible buds after 57 days).

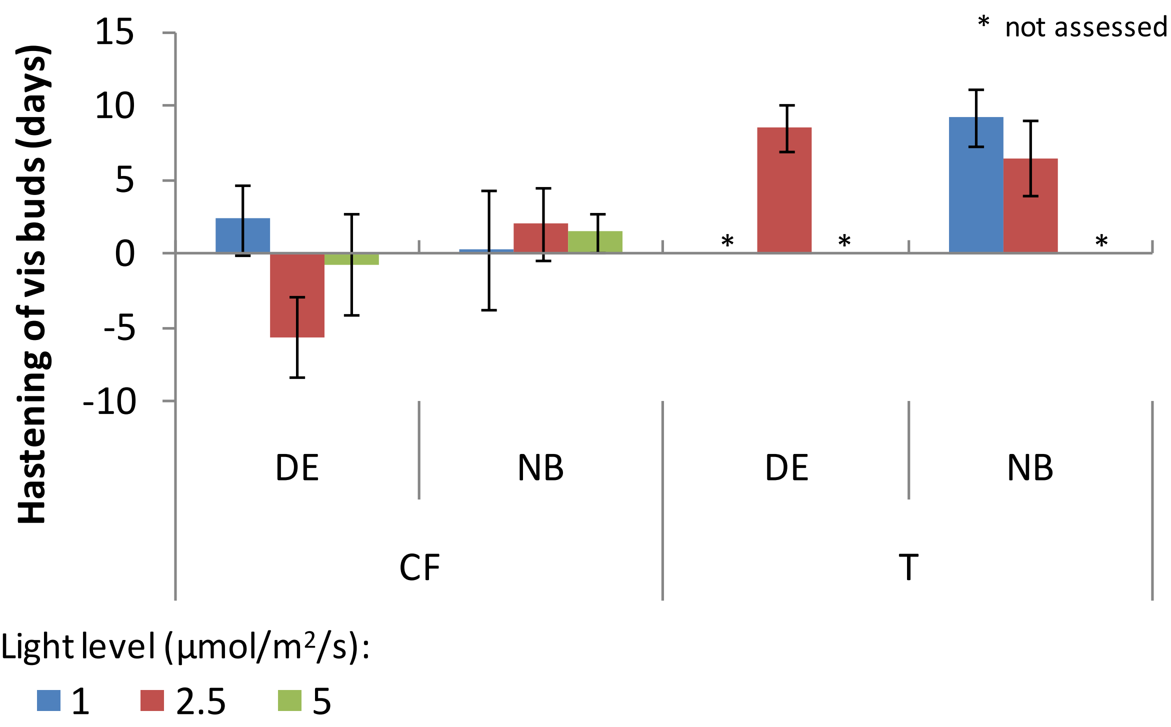


Figure 39. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time of bud appearance relative to that of the short day treatment. (SEM represented by error bars)

Plants grown with T NB developed visible buds 39 to 59 days from starting treatments (compared with 57 days for SD plants in cabinets) with light level having no significant impact on this time (figure 40). Visible buds developed after 39 to 64 days in the CF DE and CF NB treatments and light level had no significant influence over the time for visible buds appearing.

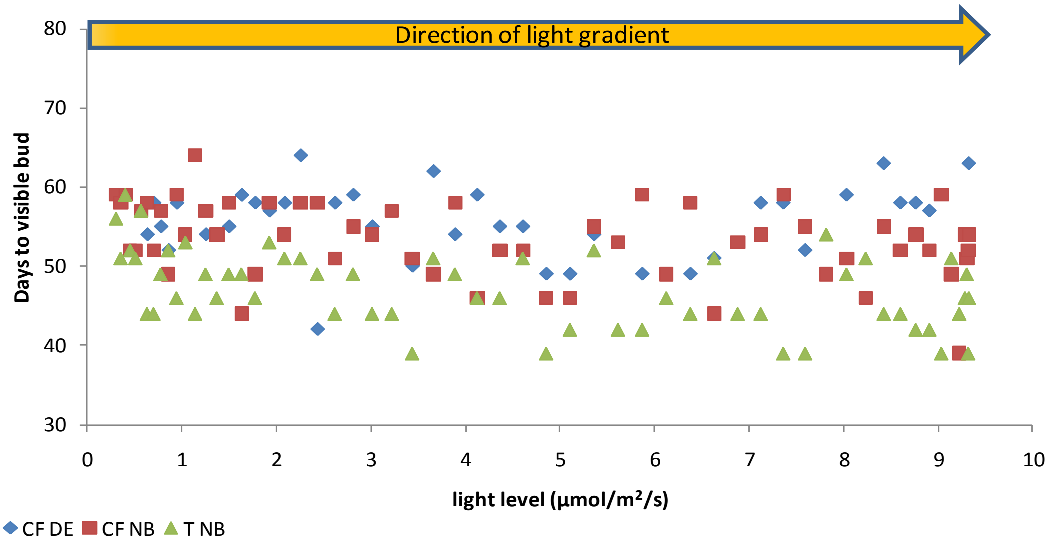


Figure 40. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for visible buds to develop for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

Pansy Majestic Giant Purple – development of flowers

Along with hastening the initial appearance of buds, T DE and NB significantly decreased flower development time (by 9-11 days) compared with the SD control (figure 41). The CF treatments had no significant influence over the time taken to develop flowers compared with the SD control.

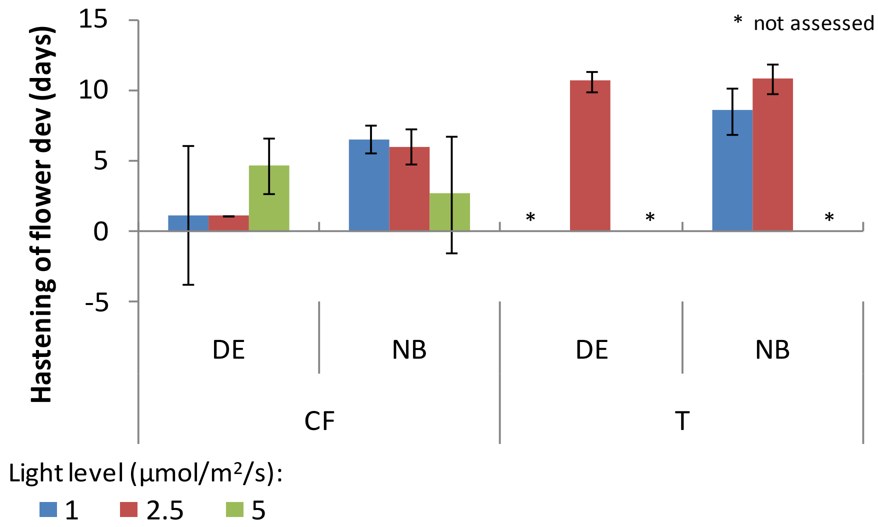


Figure 41. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time for flower development relative to that of the short day treatment. Negative numbers indicate where the lighting treatments delayed flower development. (SEM represented by error bars)

Buds developed into flowers within 11 to 26 days on plants grown with a T NB (compared with 26 days for the SD treatment in cabinets); light level had no significant impact on this time (figure 42). The range of times for development of visible buds for CF treatments was greater overall, with buds developing after 11 to 39 days across the DE and NB treatments. Light level also had no significant influence over the time for visible buds to develop in the two CF treatments.

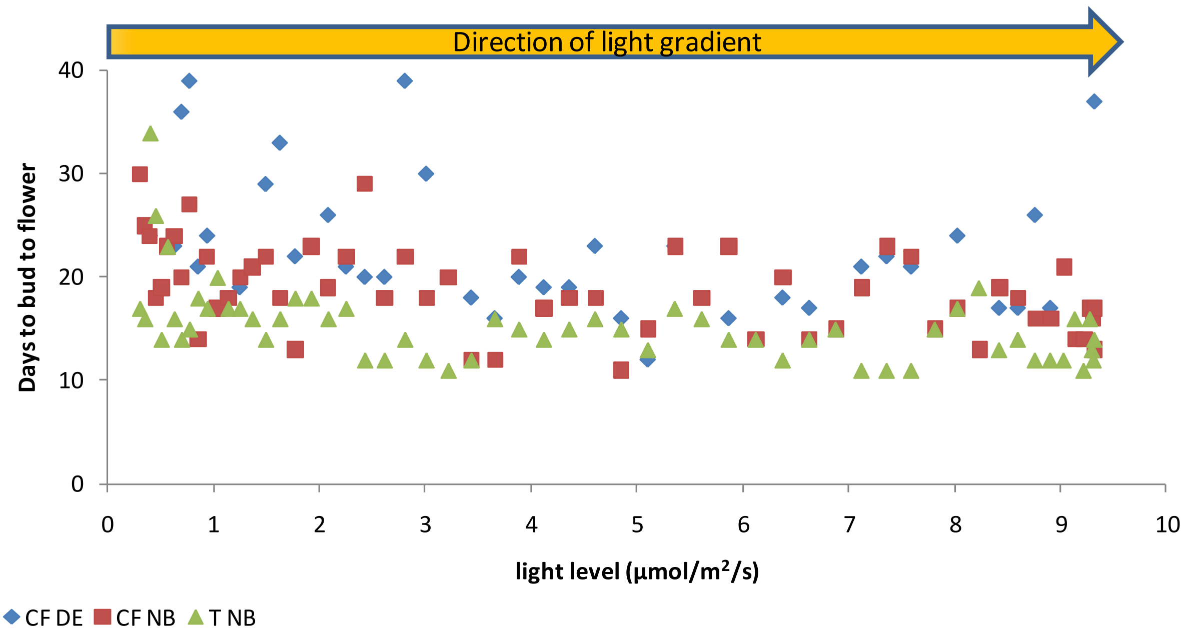


Figure 42. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for buds to develop into flowers for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 µmol/m^2/s are presented in figure 43. T DE and NB resulted in the earliest flowering, hastening both the initial development of visible buds and the development of buds into flowers. CF NB and DE were ineffective at hastening flowering.

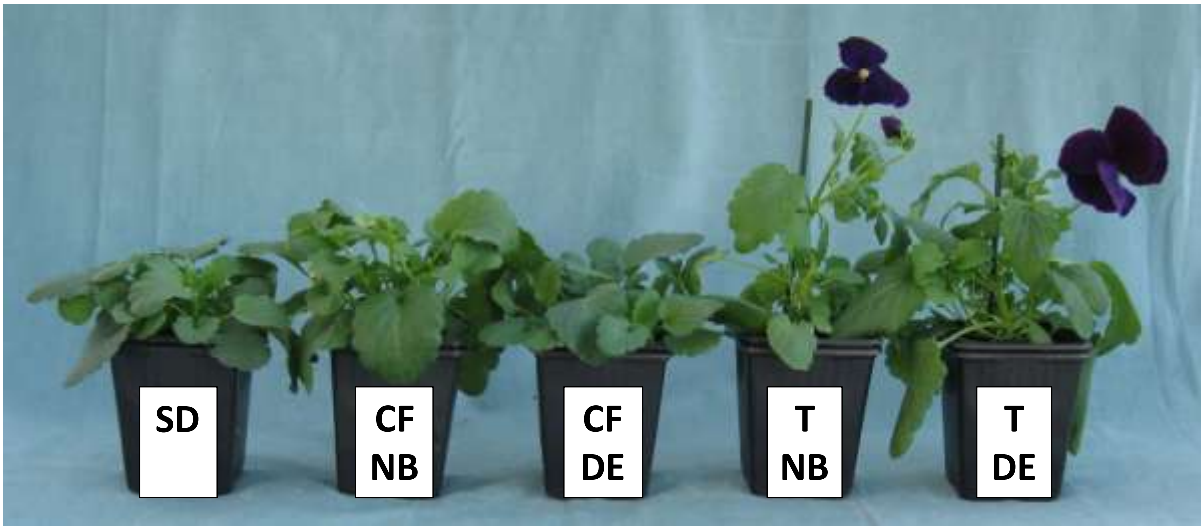


Figure 43. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 µmol/m^2/s on pansy (Majestic Giant Purple)

Petunia Express Salmon – development of visible buds

Plants grown in SD developed visible buds after an average of 93 days and all LD treatments significantly reduced this time (figure 44). T DE reduced time to visible buds by an average of 50 days (i.e. producing buds in 43 days) with T NB hastening the development of visible buds by 40-43 days. CF also resulted in a significant reduction in time to visible buds with an overall saving of around 29 to 37 days with DE and NB treatments comparable to each other in effectiveness. Light level had no significant influence within the range tested.

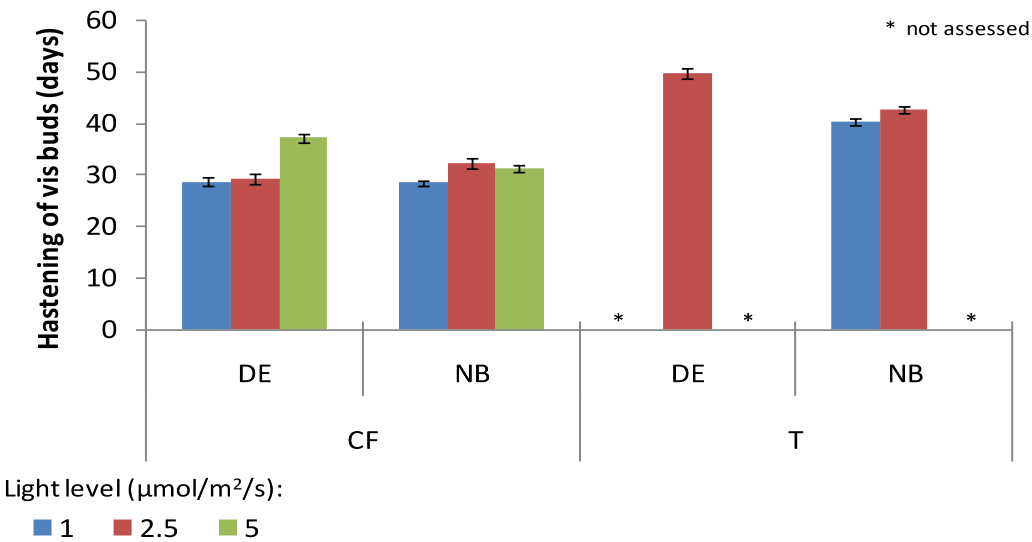


Figure 44. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time of bud appearance relative to that of the short day treatment. (SEM represented by error bars)

Days to visible bud appeared to reduce as light level along the gradient increased for the T NB treatment and a significant correlation found between these parameters for this treatment (figure 45). However even at the lowest end of the T NB gradient, visible buds appeared after 61 days which represents a significant reduction in comparison with the 93 days taken for the control plants to reach this stage. A similar, but less pronounced trend is apparent for the CF DE treatment whilst CF NB produced visible buds in a similar amount of time across the range of light levels created by the gradient.

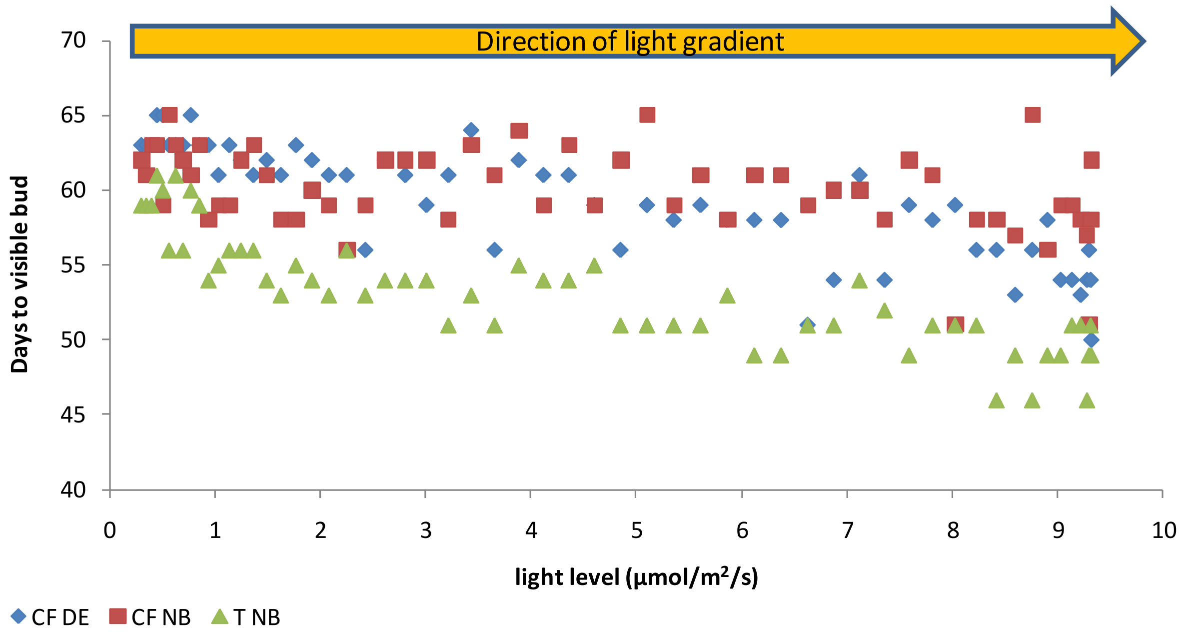


Figure 45. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for visible buds to develop for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

Petunia Express Salmon – development of flowers

Flower development time was more variable across the treatments, as indicated by the large SEM bars in figure 46 and in fact none of the treatments had a significant influence over flower development time from first visible bud stage.

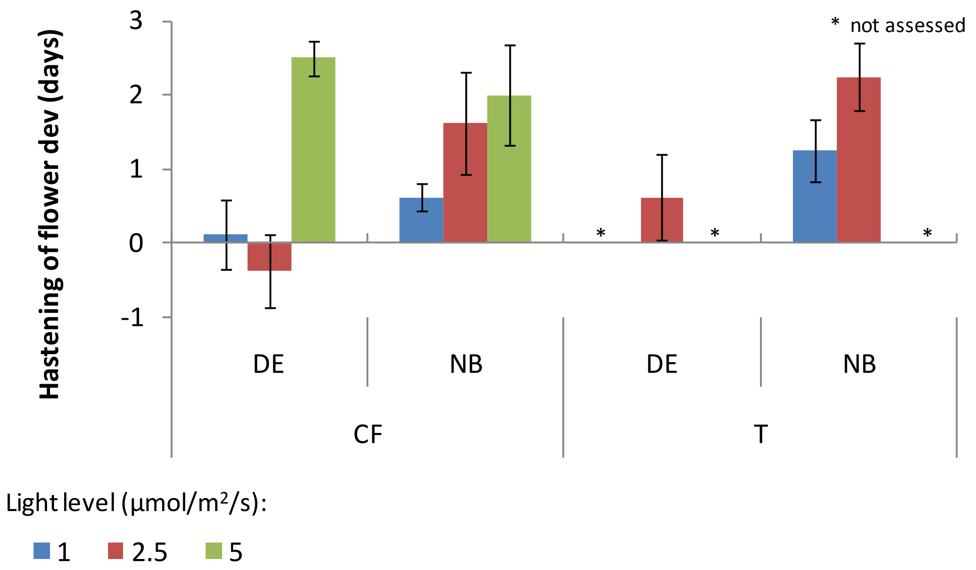


Figure 46. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time to the development of open flowers. (SEM represented by error bars)

There were no significant differences in the time taken for buds to develop into flowers across the three LD treatments and the range of light levels included in the light gradient experiments (figure 47). Hence buds developed into flowers in 7 to 16 days across the range of LD treatments which is comparable to the 14 days average figure for the SD control.

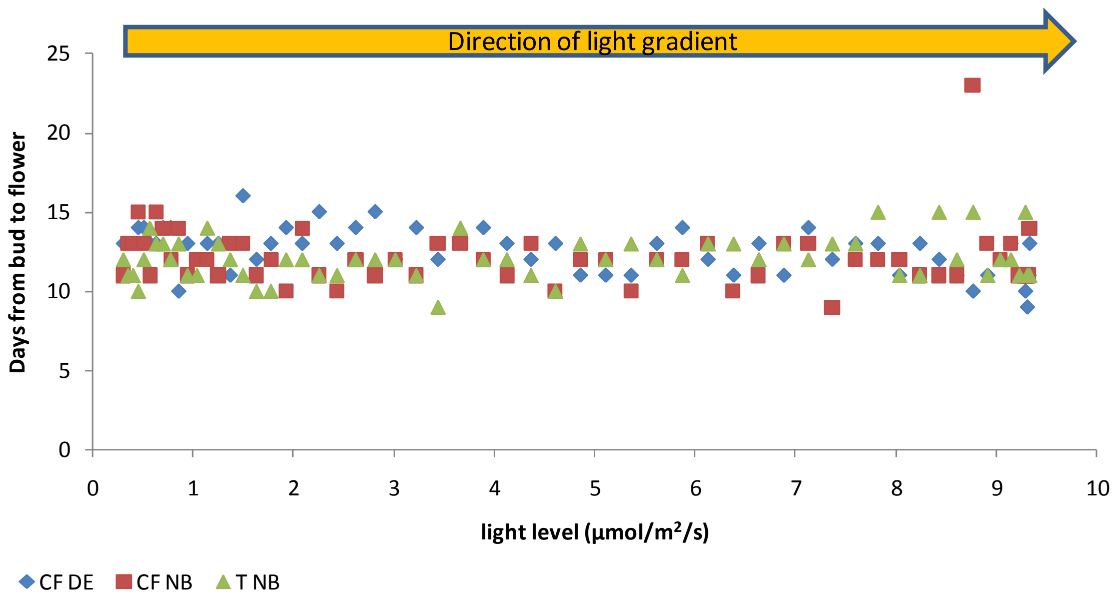


Figure 47. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for buds to develop into flowers for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 µmol/m^2/s are presented in figure 48. T DE and NB resulted in the earliest flowering. CF NB and DE were less effective at hastening flowering.

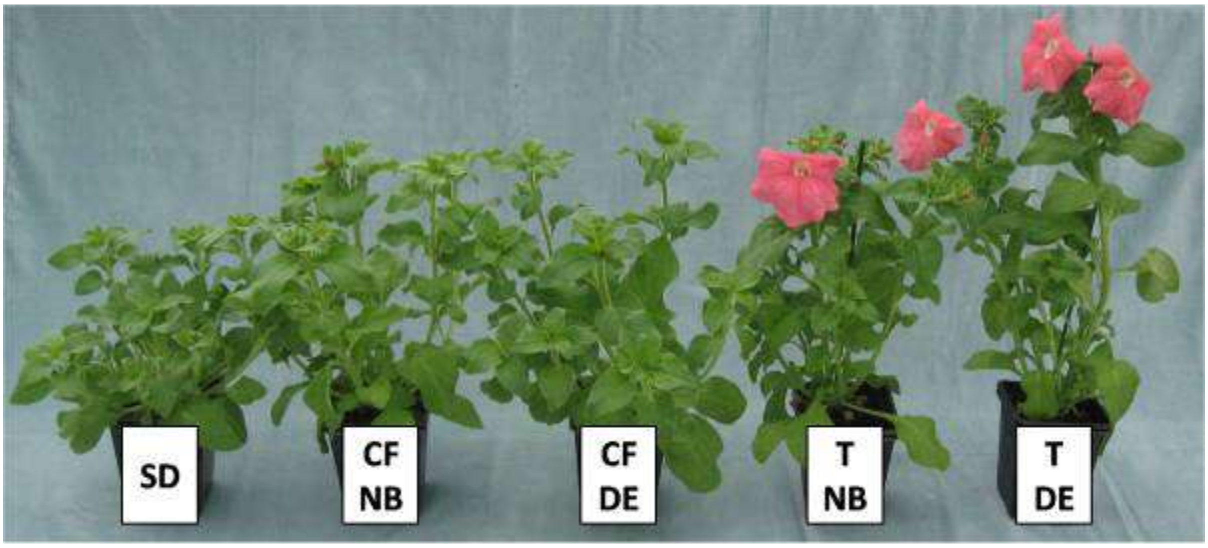


Figure 48. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 µmol/m^2/s on petunia (Express Salmon)

Poinsettia Prestige Early Red – development of red bracts

Plants developed red bracts/leaves 41 days from the start of treatments when grown in SD (figure 49). All LD treatments significantly delayed the development of red colour and not all replicate pots had started to colour by the end of the experiment. Less delay resulted from CF DE and all replicates are included in the average data presented. For the remaining LD treatments, which were slower to develop colour, average values have been taken from those pots producing red colour by the end of the experiment. Actual delay is therefore likely to have been longer than the data presented here but since delays of 80 to 100 days resulted from the CF NB, T DE and T NB treatments it is clear that all of these treatments would be effective in the manipulation of day length required in commercial poinsettia production.

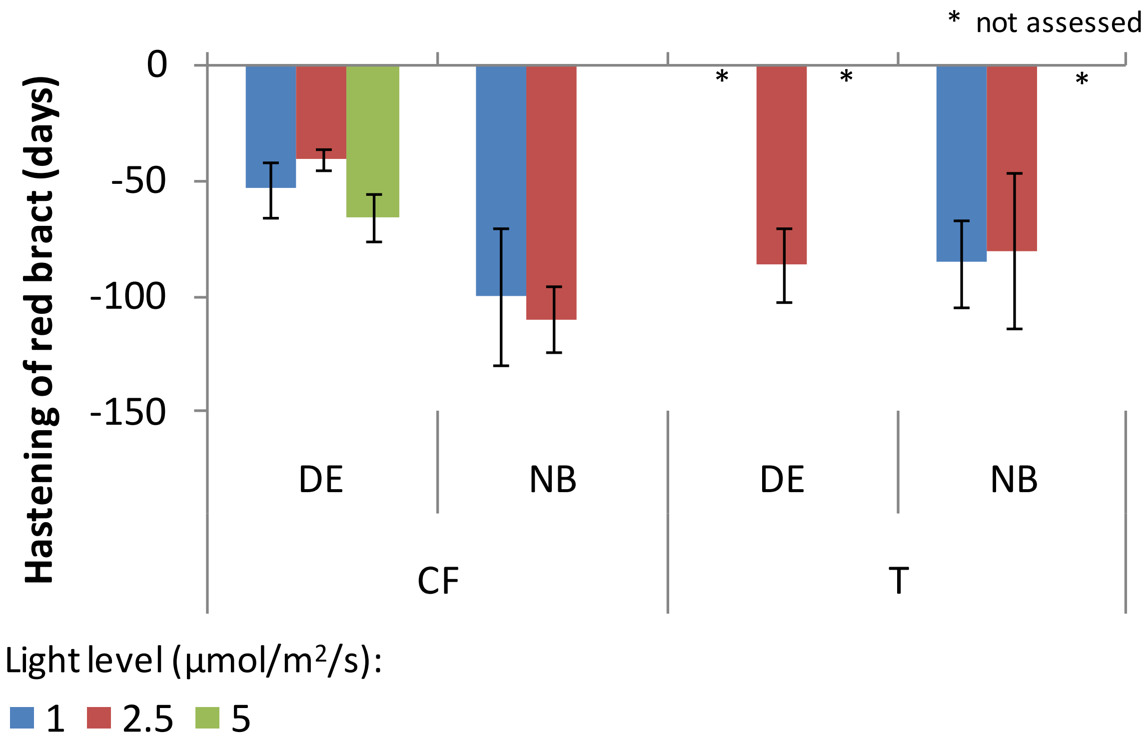


Figure 49. The effect of lamp type, LD treatment (night-break (NB) or day-extension (DE)) and light level on the time to the development of red bracts/leaves. (SEM represented by error bars)

Sufficient plants in the CF DE treatment had produced colour for light level effects to be assessed in the light gradient experiments (figure 50) and light level did not influence the time to red bract/leaf colour development within this treatment. There are insufficient data available for the T NB and CF NB treatments for the effects of light level to be determined although at the lower end of the light gradient (around 0.3 µmol/m^2/s) days to red bracts/leaves for the plants that had developed colour in these treatments were equivalent to or greater than those recorded for the CF DE treatment (i.e. generally greater than 60 days) which represents a delay in comparison with the SD control in the photoperiod cabinets (at 41 days to red colour development).

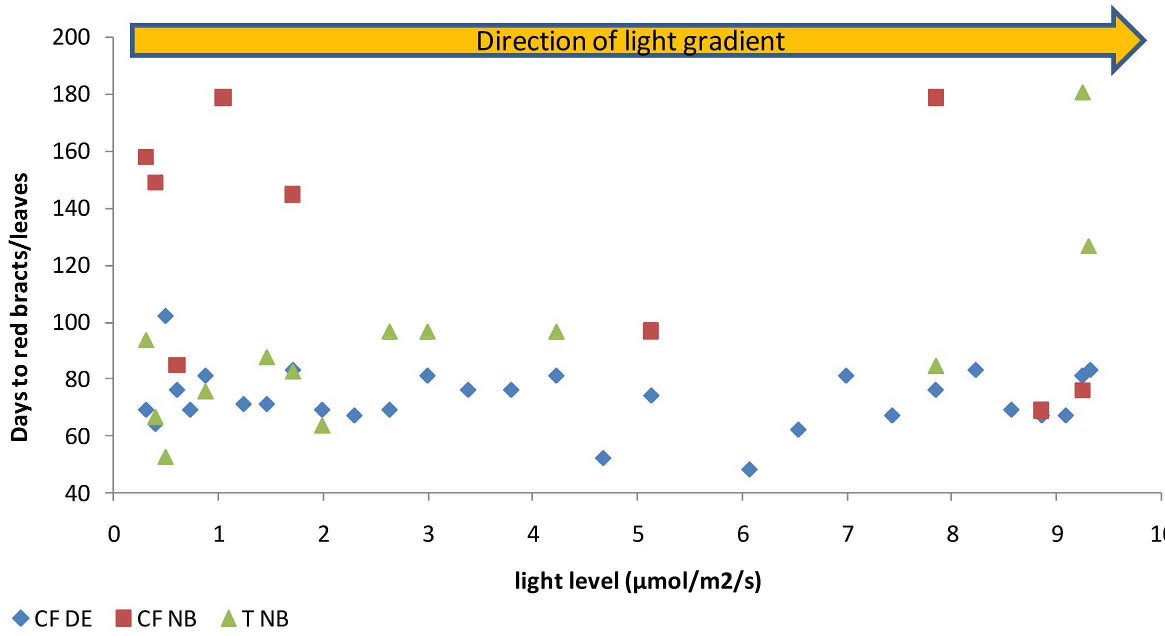


Figure 50. The effect of lamp type (compact fluorescent (CF) or tungsten (T)) and LD treatment (night break (NB) or day extension (DE)) on the time taken for bracts/leaves to develop into red colour for a range of light levels delivered along a gradient spanning the range 0.3 to 9.3 µmol/m^2/s

Plants in SD developed visible cyathia 87 days on average from the start of treatments. There was insufficient cyathia development in the LD treatments by the end of the experiment for a balanced assessment to be carried out. The CF DE treatment had the greatest incidence of cyathia development and had delayed this process by around 40 days (i.e. developing visible cyathia after 127 days in treatments). The remaining LD treatments resulted in delays in excess of this level with at least half of replicates still to develop cyathia 100 days after cyathia had developed on SD control plants.

A visual summary of the effects of lamp type and also LD type at a light level of 2.5 µmol/m^2/s are presented in figure 51. The SD treatment produced the earliest development of red colour (and also cyathia). All LD treatments delayed bract colour and subsequent cyathia development and CF DE was the least effective treatment in causing delay whilst CF NB, T NB and T DE resulted in comparable delays to each other.

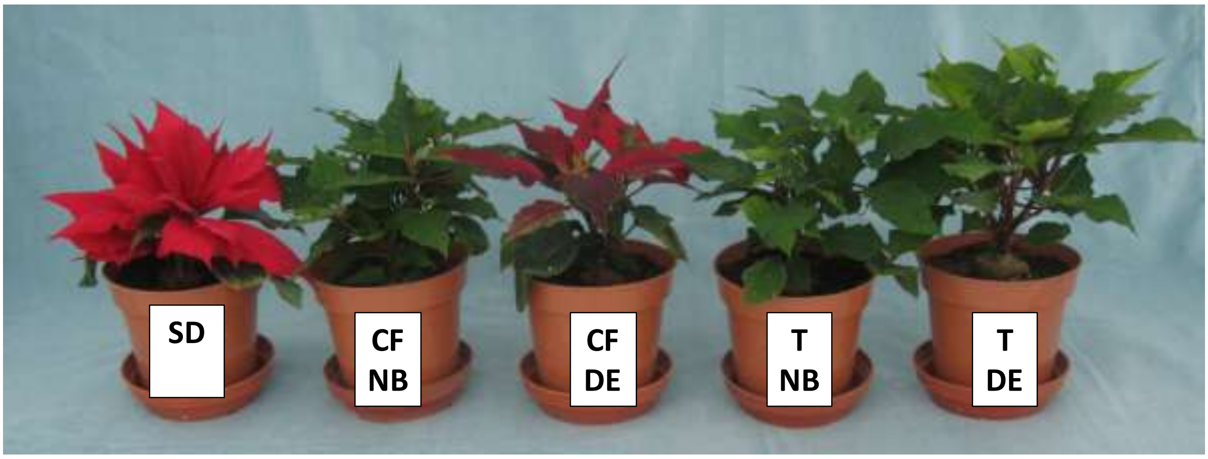


Figure 51. The effect of night-break (NB) and day-extension (DE) lighting with compact fluorescent (CF) and tungsten (T) lamps at 2.5 µmol/m^2/s on poinsettia (Prestige Early Red)

Discussion

The data included in this report for time to the development of buds and then flowers is based on definitions for these stages as outlined in Appendix I which form a reproducible and robust measure of a set stage but may be different to stages defined in commercial marketing specifications. For example, it is likely that our visible bud stage is earlier than might be the case for commercial marketing of plants with buds since our definition is based on the earliest positive sign of budding on a plant rather than more advanced budding which may be visible on majority of shoots across the whole of a plant. Furthermore the timings are based on time in treatments, which for majority of species started at the potting on stage (i.e. for either rooted cuttings or plug plants). However begonias and Christmas cactus were late additions to the project and were partially grown in commercial conditions prior to starting treatments which means time to flowering in treatments will appear shorter than might be expected from commercial experience. Poinsettias were also grown in LD following potting and prior to starting treatments in order to increase plant size prior to inducing flowering.

Response to the types of LD lighting treatments tested varied with species but overall lamp type and to some extent type of LD (i.e. DE or NB) was more important than light level within the range tested (down to 0.3 µmol/m^2/s).

Overall it is clear that there is no single CF solution which will satisfy the needs of all species when it comes to making the switch away from tungsten lighting to manipulate photoperiod.

It is also not possible to generalize according to whether the crop is a SD or LD response type.

Three of the short day species (i.e. where the LD treatments would be expected to delay flowering), responded as well to the CF LD treatments as they did to the equivalent T LD treatments. These were **chrysanthemum** (Tampico White), **poinsettia** (Prestige Early Red) and **begonia** (Illumination Red). For **Christmas cactus** however T DE resulted in the best delay which was a continuation of the treatment these plants had received during initial production at the commercial nursery. While T NB and CF NB and CF DE all delayed flowering of Christmas cactus compared with the SD treatment they were less effective than the T DE treatment. Christmas cactus was also the only species which appeared to be influenced by light level with a decrease in delay when the CF or T intensity was below 1 $\mu mol/m^2/s$; however there was no light gradient T DE treatment with which to test light level of the most effective treatment for this species.

Results for the LD species were more varied:

For **fuchsia**, all LD treatments promoted flowering equally well.

For **antirrhinum** (Red Bells) and **pansy** (Majestic Giant Purple), only the T treatments were effective in promoting flowering.

For **lisianthus** (Forever Purple and Florida Silver) and **petunia** (Express Salmon), T lighting was more effective than CF lighting and also T DE was better than T NB. For both of these species, CF lighting did delay flowering compared with the SD control and for lisianthus CF NB was better than CF DE whilst for petunia both LD types were equivalent to each other when using CF lamps.

Where CF lamps were not effective, increasing the light level from these lamps up to 9.3 $\mu mol/m^2/s$ was not sufficient to improve response. Hence the solution to improving effectiveness is likely to require a change in spectral output rather than an increase in the number of lamps used. Interestingly where treatments were effective, response was also generally found down to the lowest end of the gradients (i.e. 0.3 $\mu mol/m^2/s$) and hence, at least for the varieties tested here, effective CF LD lighting may not need to be at high levels. This result was not expected at the outset of this project and for example, some of the earlier varieties of chrysanthemum tested at GCRI would not have responded to the lower levels in the gradient experiments. Of course in practice, growers will often need a lighting system suitable for use with a range of species and varieties which will at least require further in house trials.

There next phase of work initially planned for this project aimed to look first T and CF lamps in opposing light gradients to enable the effects of R:FR and intensity to be separated. However since the light quality has been the dominant factor in these initial experiments it has been agreed that resource should instead be directed into a larger photoperiod cabinet experiment looking at red and far red light which are associated with control of photoperiod. Given the problem of plant stretching commonly associated with the red light in tungsten lighting, these future experiments may also include blue LEDs which would be expected to help balance the plant stretch responses associated with red light. The aim of these experiments will be to identify suitable light quality for controlling flowering whilst maintaining plant quality in a range of species (with both LD and SD types represented). Wherever possible, lamps being developed for the Horticulture industry will be included in order to identify useable recommendations for growers.

It should also be noted that the experiments reported here were carried out in either 8 hour days within the photoperiod cabinets with day extension or night break for LD treatments, or in natural SD on the light gradient benches during the period November 2009 to February 2010 for majority of species (extending to May for some poinsettia and lisianthus treatments). Photoperiodic response to end of day lighting, at least in terms of shade avoidance and hence plant height, may be influenced by light integral which will depend on the actual length of SD given and not just R:FR ratio (e.g. Lund et al, 2007) and this will need to be considered when extrapolating from the results presented here. Lund et al have also demonstrated that quantity of R and FR may influence photoperiod response beyond the R:FR ratio effects that are well established. Hence when maintaining a R:FR ratio of 2.4 or 0.7 plants (chrysanthemum) were taller when FR was at 1 μmol/m^2/s and R was at 2.4 or 0.7 μmol/m^2/s respectively compared with maintaining R at 1 μmol/m^2/s and varying FR. It will be important to consider these findings when designing future treatments within this project and within any future associated work.

Conclusions

A cautious approach should be taken with regards to the replacement of tungsten with CF lamps as just over half of the species tested did not respond effectively to the light spectrum from CF lamps. This was the case even when the light level was increased to twice that of the current commercial norm. This is probably because the CF lamps lack far-red light, and this appears to be more important for DE than NB lighting.

While CF lamps were suitable for replacing tungsten in chrysanthemum, poinsettia, fuchsia and begonia, LEDs may be available for use soon and have potential to be more efficient alternatives by providing the light quality required. Based on the results from this work a combination of red (~660 nm) and far-red (~730 nm) light will probably give a good response for most species, although in some species, such as chrysanthemum, the far-red could be reduced especially if stretching is a concern.

The aim of subsequent experiments within this project will be to test LED lamps of different wavelengths and compare their efficacy with tungsten lamps.

Technology Transfer

Energy-saving bulbs: not such a bright idea. HDC News No. 165, July/August 2010.
Presentation to the PO Panel meeting, 23 February 2010, WHRI Wellesbourne.
Presentation to the LED/Thermal Imagery Seminar, 17-18 February 2010, WHRI Wellesbourne.

References

Lund, J.B., Blom, T.J. and Aaslyng, J.M. (2007). End-of-day lighting with different red/far-red ratios using light emitting diodes affects plant growth of *Chrysanthemum x morifolium* Ramat. 'Coral Charm'. HortScience 42(7); 1609-1611.

Appendix I – Detailed plans of treatments

Lighting in Growth Chambers

Bulbs were evenly distributed in growth chambers with Wattage altered n order to vary light level as detailed below. These plans were designed to produce even distribution of light rather than optimum energy efficiency.

Light level	Bulbs used
Tungsten treatments	
1 W/m^2	1 x 40W and 1 x 60W
2.5 W/m^2	2 x 25W
Compact Fluorescent treatments	
1 W/m^2	1 x Osram Dulux EL Economy 6W 1 x Osram Dulux S 11W
2.5 W/m^2	1 x Osram Dulux S 5W 1 x Osram Dulux S 7W 2 x Osram Dulux EL Economy 21W
5 W/m^2	4 x Osram Dulux S 5W with 50% shade

Lighting on benches to produce a gradient of declining light level

The table below details how bulbs were positioned along benches in order to generate gradients of declining light level along the bench. The numbers within each box indicate the position and Wattage of each bulb. A mixture of CF bulb types were required to produce an even gradient. Each of the bulb types used are detailed below the table. Yellow highlighted numbers indicate where reflectors were used with the bulb.

Distance along bench (cm)	Bulb position, wattage and reflector position														
	CF Night Break					CF Day Extension					T Day Extension				
-50		23W	23W	23W			30W		30W			60W		60W	
0	23W	23W		23W	23W	23W	23W		23W	23W	60W		60W		60W
50	23W				23W	23W				23W	60W	60W	60W	60W	60W
100	11W		23W		11W	11W		23W		11W					
150	8W		23W		8W	7W		23W		7W	60W				60W
200			23 W					23W					40W		
250											40W				40W
300			23 W					23W					40W		
350											40W				40W
400											25W		25W		25W
			23W					21W							
450															
500															
550															
600															
650															

CF Bulbs Used:

- Philiips Genie 8W
- Philips Genie 11W
- Osram Dulux EL Economy 21W/827
- Osram Dulux EL 23W/827
- Osram Dulux EL 30W/827

Appendix II: Definition of Bud and Flower stages

Buds. **Flowers**

Anthirrinum

1-2 mm diameter

As soon as inside of flower is visible

Petunia

2-3 mm diameter

As soon as inside of flower is visible

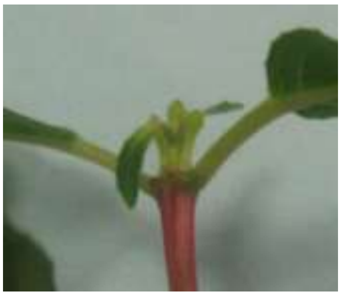
Pansy

approx. 7 mm long

As soon as inside of flower is visible

Buds: **Flowers:**

Fuchsia



1-2 mm long

As soon as one sepal has split from the

Others

Chrysanthemum

4 mm diameter

Flower stage 6

Autonomous flowering. Plant has started to branch. The last leaf before the bud has completely unfolded. The tiny bud and “pointed” leaf are visible.

Buds: **Flowers:**

Christmas cactus

1-2 mm long

As soon as pink stigma is visible

Red colour in poinsettia

Cyathia

Recorded as soon as leaves have unfolded

Buds: **Flowers:**

Lisianthus

Forever Blue

Florida Silver

Appendix III: Data for photoperiod cabinet experiments

Antirrhinum Days to visible bud		Lamp					
		None	Compact fluorescent			Tungsten	
Short day-Long day \ PPFD		0	1	2.5	5	1	2.5
Short day	Mean	56.4					
	S.E.M.	0.84					
	No. Reps	23					
Day extension	Mean		59.5	54.1	48.3		38.0
	S.E.M.		0.98	1.73	1.33		1.34
	No. Reps		8	8	8		8
Night break	Mean		52.8	49.1	54.5	43.6	44.4
	S.E.M.		1.52	1.08	1.35	0.50	0.26
	No. Reps		8	8	8	8	8

Antirrhinum Days to flower		Lamp					
		None	Compact fluorescent			Tungsten	
Short day-Long day \ PPFD		0	1	2.5	5	1	2.5
Short day	Mean	83.0					
	S.E.M.	0.98					
	No. Reps	23					
Day extension	Mean		85.0	79.9	74.6		57.3
	S.E.M.		1.15	1.81	1.57		1.41
	No. Reps		8	8	8		8
Night break	Mean		78.3	74.6	79.1	66.5	64.6
	S.E.M.		1.52	1.03	1.25	0.63	0.60
	No. Reps		8	8	8	8	8

Begonia Tuber fresh weight (g)		Lamp					
		None	Compact fluorescent			Tungsten	
Short day-Long day	PPFD	0	1	2.5	5	1	2.5
Short day	Mean	0.291					
	S.E.M.	0.0159					
	No. Reps	24					
Day extension	Mean		0.134	0.127	0.175		0.138
	S.E.M.		0.0134	0.0152	0.0140		0.0162
	No. Reps		8	8	8		8
Night break	Mean		0.100	0.139	0.125	0.134	0.121
	S.E.M.		0.0169	0.0183	0.0187	0.0179	0.0186
	No. Reps		8	8	8	8	8

Begonia Tuber diameter (mm)		Lamp					
		None	Compact fluorescent			Tungsten	
Short day-Long day	PPFD	0	1	2.5	5	1	2.5
Short day	Mean	9.2					
	S.E.M.	0.239					
	No. Reps	24					
Day extension	Mean		7.0	6.5	7.2		6.7
	S.E.M.		0.435	0.349	0.280		0.369
	No. Reps		8	8	8		8
Night break	Mean		6.6	6.6	6.8	7.0	6.8
	S.E.M.		0.295	0.489	0.464	0.409	0.360
	No. Reps		8	8	8	8	8

Begonia Total fresh weight (g)		Lamp					
		None	Compact fluorescent			Tungsten	
Short day-Long day	PPFD	0	1	2.5	5	1	2.5
Short day	Mean	0.567					
	S.E.M.	0.0272					
	No. Reps	24					
Day extension	Mean		1.145	0.981	1.302		1.101
	S.E.M.		0.0753	0.0420	0.0465		0.0699
	No. Reps		8	8	8		8
Night break	Mean		1.122	1.168	1.577	1.535	1.096
	S.E.M.		0.1215	0.0455	0.1380	0.1141	0.0536
	No. Reps		8	8	8	8	8

Christmas Cactus Days to visible bud		Lamp					
		None	**Compact fluorescent**			**Tungsten**	
PPFD / **Short day-Long day**		**0**	**1**	**2.5**	**5**	**1**	**2.5**
Short day	**Mean**	22.0					
	S.E.M.	-					
	No. Reps	24					
Day extension	**Mean**		33.0	31.0	31.1		39.3
	S.E.M.		0.89	1.05	1.04		1.29
	No. Reps		8	8	8		7
Night break	**Mean**		26.0	27.9	28.3	31.1	28.1
	S.E.M.		1.05	0.87	0.25	0.74	1.06
	No. Reps		8	8	8	8	8
	S.E.M.						
	No. Reps						

Christmas Cactus Days to flower		Lamp					
		None	**Compact fluorescent**			**Tungsten**	
PPFD / **Short day-Long day**		**0**	**1**	**2.5**	**5**	**1**	**2.5**
Short day	**Mean**	71.9					
	S.E.M.	0.31					
	No. Reps	24					
Day extension	**Mean**		79.3	80.5	81.6		90.0
	S.E.M.		1.11	0.68	1.13		1.29
	No. Reps		7	8	8		6
Night break	**Mean**		76.8 0.62 8	77.9 0.58 8	78.5 0.60 8	81.0 0.85 8	77.9 0.77 8

Chrysanthemum Days to visible bud		Lamp					
		None	Compact fluorescent			Tungsten	
Short day-Long day	PPFD	0	1	2.5	5	1	2.5
Short day	Mean	24.1					
	S.E.M.	0.17					
	No. Reps	24					
Day extension	Mean		77.0	79.3	76.0		80.9
	S.E.M.		0.63	1.90	0.73		1.39
	No. Reps		8	8	8		8
Night break	Mean		77.3	77.0	75.5	85.5	83.3
	S.E.M.		1.19	0.27	0.38	2.95	1.74
	No. Reps		8	8	8	8	8

Chrysanthemum Number of leaves		Lamp					
		None	Compact fluorescent			Tungsten	
Short day-Long day	PPFD	0	1	2.5	5	1	2.5
Short day	Mean	6.9					
	S.E.M.	0.11					
	No. Reps	35					
Day extension	Mean		17.3	17.6	15.9		17.8
	S.E.M.		0.37	0.32	0.23		0.25
	No. Reps		8	8	8		8
Night break	Mean		18.4	18.1	17.5	19.8	19.3
	S.E.M.		0.32	0.23	0.27	0.41	0.16
	No. Reps		8	8	8	8	8
	S.E.M.						
	No. Reps						

Fuchsia Days to visible bud		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD Short day- Long day		0	1	2.5	5	1	2.5
Short day	Mean	>191					
	S.E.M.	-					
	No. Reps	-					
Day extension	Mean		37.4	37.6	36.3		34.3
	S.E.M.		1.18	1.19	0.37		0.49
	No. Reps		8	8	8		8
Night break	Mean		36.6 1.24 8	34.3 0.49 8	35.6 1.13 8	36.1 0.83 8	34.9 0.48 8

Fuchsia Days to flower		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD Short day- Long day		0	1	2.5	5	1	2.5
Short day	Mean	>191					
	S.E.M.	-					
	No. Reps	-					
Day extension	Mean		75.1	77.5	73.3		68.4
	S.E.M.		1.61	1.34	0.53		1.52
	No. Reps		8	8	8		8
Night break	Mean		74.3	71.4	73.4	72.8	71.0
	S.E.M.		1.71	0.86	1.52	1.08	0.65
	No. Reps		8	8	8	8	8

Lisianthus Florida Days to visible bud		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD / Short day-Long day		0	1	2.5	5	1	2.5
Short day	Mean	177.5					
	S.E.M.	1.74					
	No. Reps	23					
Day extension	Mean		168.5	171.0	165.9		122.4
	S.E.M.		2.01	2.43	1.04		3.28
	No. Reps		8	8	8		8
Night break	Mean		165.1	158.9	160.0	151.5	138.1
	S.E.M.		1.14	1.72	3.28	1.85	3.80
	No. Reps		8	8	8	8	8
	S.E.M.						
	No. Reps						

Lisianthus Florida Days to flower		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD / Short day-Long day		0	1	2.5	5	1	2.5
Short day	Mean	>191.0					
	S.E.M.	-					
	No. Reps	-					
Day extension	Mean		>191.0	>191.0	>191.0		175.3
	S.E.M.		-	-	-		3.33
	No. Reps		-	-	-		8
Night break	Mean		>191.0 - -	>191.0 - -	>191.0 - -	>191.1 - -	>185.3 - -

Lisianthus Forever Days to visible bud		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD / Short day-Long day		0	1	2.5	5	1	2.5
Short day	Mean	159.0					
	S.E.M.	1.17					
	No. Reps	24					
Day extension	Mean		155.8	158.6	156.0		117.3
	S.E.M.		2.56	1.11	1.60		3.55
	No. Reps		8	7	8		8
Night break	Mean		157.0	139.9	150.5	133.5	130.1
	S.E.M.		1.49	3.32	1.22	3.63	2.13
	No. Reps		8	8	8	8	8

Lisianthus Forever Days to flower		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD / Short day-Long day		0	1	2.5	5	1	2.5
Short day	Mean	>191.0					
	S.E.M.	-					
	No. Reps	-					
Day extension	Mean		>191.0	>191.0	>191.0		164.5
	S.E.M.		-	-	-		3.06
	No. Reps		-	-	-		8
Night break	Mean		>191.0	>186.6	>191.0	>182.0	>178.1
	S.E.M.		-	-	-	-	-
	No. Reps		-	-	-	-	-

Pansy (without aborted) Days to visible bud		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD / Short day-Long day		0	1	2.5	5	1	2.5
Short day	Mean	56.7					
	S.E.M.	0.75					
	No. Reps	12					
Day extension	Mean		54.3	62.3	57.3		48.1
	S.E.M.		2.33	2.73	3.45		1.60
	No. Reps		3	3	6		8
Night break	Mean		56.4	54.7	55.2	47.4	50.1
	S.E.M.		4.03	2.44	1.35	1.88	2.58
	No. Reps		5	6	6	8	8

Pansy (without aborted) Days to flower		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD / Short day-Long day		0	1	2.5	5	1	2.5
Short day	Mean	82.8					
	S.E.M.	1.32					
	No. Reps	12					
Day extension	Mean		79.3	85.5	78.8		63.6
	S.E.M.		7.12	2.47	4.47		1.77
	No. Reps		3	4	6		8
Night break	Mean		76.0	74.8	78.7	65.0	65.5
	S.E.M.		4.64	3.53	4.56	1.60	3.32
	No. Reps		5	6	6	8	8

Petunia Days to visible bud		Lamp					
		None	Compact fluorescent			Tungsten	
Short day-Long day	PPFD	0	1	2.5	5	1	2.5
Short day	Mean	92.7					
	S.E.M.	0.80					
	No. Reps	24					
Day extension	Mean		63.9	63.5	55.4		42.8
	S.E.M.		0.95	0.98	0.88		0.98
	No. Reps		8	8	8		8
Night break	Mean		64.1	60.3	61.4	52.3	50.0
	S.E.M.		0.58	0.96	0.73	0.59	0.63
	No. Reps		8	8	8	8	8

Petunia Days to flower		Lamp					
		None	Compact fluorescent			Tungsten	
Short day-Long day	PPFD	0	1	2.5	5	1	2.5
Short day	Mean	106.3					
	S.E.M.	0.86					
	No. Reps	24					
Day extension	Mean		77.4	77.5	66.5		55.8
	S.E.M.		1.32	0.93	1.02		1.10
	No. Reps		8	8	8		8
Night break	Mean		77.1 0.61 8	72.2 0.92 8	73.0 1.16 8	64.6 0.63 8	61.4 0.38 8

Poinsettia Days to red bract		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD / Short day-Long day		0	1	2.5	5	1	2.5
Short day	Mean	41.3					
	S.E.M.	0.20					
	No. Reps	24					
Day extension	Mean		94.9	81.4	106.9		127.3
	S.E.M.		11.70	4.51	9.81		15.83
	No. Reps		8	8	8		4
Night break	Mean		141.5	151.0	>191	126.8	121.5
	S.E.M.		29.65	14.00	-	18.79	33.50
	No. Reps		4	2	-	5	2

Poinsettia Days to cyathia		Lamp					
		None	Compact fluorescent			Tungsten	
PPFD / Short day-Long day		0	1	2.5	5	1	2.5
Short day	Mean	87.4					
	S.E.M.	4.61					
	No. Reps	22					
Day extension	Mean		159.3	126.5	145.0		>191
	S.E.M.		5.67	7.71	-		-
	No. Reps		3	6	1		-
Night break	Mean		>191 - -	>191 - -	>191 - -	177.0 0.99 2	>191 - -

Appendix III: Data for light gradient experiments

Antirrhinum	Days to visible bud			Days to flower		
PPFD ($\mu mol/m^2/s$)	CF DE	CF NB	T NB	CF DE	CF NB	T NB
SD		56.4			83	
0.30	50	45	45	71	65	64
0.35	53	46	41	77	70	59
0.40	54	45	45	79	67	64
0.45	53	46	46	78	68	67
0.51	52	47	46	75	72	64
0.57	47	47	42	70	69	61
0.63	47	47	40	71	70	60
0.70	47	46	42	71	68	61
0.77	48	47	40	73	68	58
0.86	47	50	43	71	74	62
0.94	45	50	37	66	73	58
1.04	50	50	42	74	72	61
1.14	47	47	40	70	70	59
1.25	50	43	42	74	65	60
1.37	56	45	42	79	67	62
1.50	47	47	43	71	70	62
1.63	45	53	42	68	75	62
1.77	46	46	42	69	70	61
1.93	47	54	43	72	80	63
2.09	53	57	42	77	81	62
2.25	53	50	40	79	75	58
2.43	47	50	42	70	76	60
2.62	54	46	44	75	68	64
2.81	47	50	40	72	75	59
3.01	54		42	77		62
3.22	45		42	67		63
3.44	56	54	45	81	79	65
3.66	61	50	45	86	73	65
3.89	42	47	40	63	68	59
4.12	49	50	43	75	74	63
4.36	46	52	43	70	74	65
4.61	48	52	42	74	75	61
4.86	48	53	42	75	76	63
5.11	46	54	42	68	75	60
5.36	54	47	44	79	70	64
5.62	49	54	42	74	76	61
5.87	47	61		72	85	
6.13	48	54	43	74	76	62
6.38	49	53	42	74	77	60
6.63	49	52	45	72	74	67
6.88	54	46	42	78	68	63
7.13	45	47	42	82	69	61
7.36	31	45	42	54	67	60
7.60	47	46	42	72	70	62
7.82	63	45	42	89	70	61
8.03	48	45	42	75	67	61
8.24	50	47	40	76	68	60
8.43	47	46	40	72	68	60
8.60	45	48	40	66	70	60
8.77	48	46	40	75	68	60
8.91	45	48	42	66	71	62
9.04	45	50	43	70	74	61
9.14	43	46	48	65	68	71
9.23	45	48	40	68	72	60
9.29	45	50	40	67		60
9.32	48	48	35	74	74	54
9.33	48	46	42	72	68	60
9.31	48	45	42	74	67	61

Begonia	Tuber fresh weight (g)			Tuber diameter (mm)			Total plant fresh weight (g)		
PPFD ($\mu mol/m^2/s$)	CF DE	CF NB	T NB	CF DE	CF NB	T NB	CF DE	CF NB	T NB
SD	0.291			9.2			0.567		
0.30	0.126	0.115	0.096	6.4	6.3	5.8	1.029	0.907	1.012
1.08	0.113	0.128	0.166	6.2	6.6	7.1	1.081	0.995	1.015
2.77	0.112	0.155	0.199	6.3	6.8	7.4	0.969	0.968	1.069
5.41	0.130	0.166	0.145	6.9	7.4	7.2	0.990	1.098	1.097
8.16	0.138	0.127	0.145	7.0	6.7	6.9	0.907	0.957	1.058
9.31	0.130	0.126	0.177	7.0	6.6	6.0	1.080	1.293	0.953

Christmas Cactus	Days to visible bud			Days to flower		
PPFD ($\mu mol/m^2/s$)	CF DE	CF NB	T NB	CF DE	CF NB	T NB
SD	22			71.9		
0.30	22	22	22	67	71	66
0.37	22	22	22	72	69	67
0.44	25	22	22	76	69	68
0.52	25	28	22	78	78	74
0.60	25	25	22	80	76	74
0.70	22	25	22	76	71	75
0.80	22	22	25	75	70	78
0.92	25	25	22	75	82	73
1.05	25	28	25	75	76	75
1.20	28	22	30	83	79	84
1.36	28	25	25	79	75	78
1.53	30	30	30	83	81	80
1.73	35	28	30	89	78	80
1.94	28	28	28	75	77	79
2.16	32	28	33	87	83	81
2.41	30	28	30	83	81	79
2.66	28	28	28	81	83	92
2.94	30	25	30	88	78	78
3.23	30	30	28	83	80	77
3.53	30	32	32	83	87	90
3.84	30	25	32	82	80	83
4.17	30	30	30	91	82	79
4.51	28	28	25	78	78	79
4.85	22	30	25	76	81	78
5.20	35	28	28	89	77	80
5.55	35	28	32	87	85	83
5.91	35	28	30	84	79	79
6.26	30	25	32	85	78	82
6.61	30	30	28	83	79	78
6.96	28	28	25	85	85	81
7.29	35	28	28	90	78	83
7.62	28	28	30	80	79	83
7.92	32	28	32	84	80	84
8.21	30	30	30	83	83	79
8.48	28	28	30	81	79	79
8.71	30	28	32	80	79	85
8.92	32	30	32	83	78	80
9.09	33	28	30	91	80	79
9.21	28	25	28	78	78	81
9.30	33	32	32	83	80	79
9.33	33	28	30	85	77	83
9.31	30	28	30	81	73	79

Chysanthemum	Days to visible bud			Number of leaves		
PPFD ($\mu mol/m^2/s$)	CF DE	CF NB	T NB	CF DE	CF NB	T NB
SD	24.1			6.9		
0.30	78	76	78	18	18	17
0.40	79	78	82	17	19	19
0.50	84	86	96	19	19	21
0.62	82	86	95	18	19	20
0.76	86	88	99	19	19	21
0.93	91	88	93	19	19	20
1.12	82	80	89	19	17	19
1.34	82	89	89	19	20	20
1.59	82	94	89	19	20	19
1.88	82	82	89	18	19	20
2.20	82	77	89	19	19	19
2.55	82	86	88	18	19	19
2.93	82	86	88	18	19	20
3.34	49	89	88	17	19	19
3.78	81	82	88	17	19	18
4.24	84	82	91	17	18	21
4.72	82	81	86	18	19	18
5.21	81	81	95	18	19	20
5.71	84	77	88	18	20	19
6.21	74	76	88	17	18	20
6.71	81	77	88	18	18	19
7.19	82	74	88	17	18	19
7.65	81	72	84	17	18	18
8.08	81	80	86	18	19	18
8.46	93	77	86	18	18	19
8.79	82	78	93	18	18	20
9.05	86	74	89	18	18	19
9.23	86	78	93	18	18	19
9.32	82	71	93	18	17	19
9.31	81	82	88	19	18	18

Lisianthus Florida	Days to visible bud			Days to flower		
PPFD (µmol/m^2/s)	CF DE	CF NB	T NB	CF DE	CF NB	T NB
SD		177.5			>193	
0.30	158	155	135			184
0.35	158	150	140			191
0.40	168	150	140			186
0.45	161	150	142			189
0.51	167	155	147			
0.57	158	155	142			186
0.63	161	147	150		191	
0.70	161	155	133			180
0.77	161	150	140			184
0.86	160	150	137			190
0.94	158	155	142			190
1.04	158	150	150			
1.14	158	150	140			190
1.25	158	161	137			184
1.37	161	150	144		188	
1.50	155	155	137			180
1.63	155	155	142		191	189
1.77	161	161	144			190
1.93	155	155	140	191		190
2.09	155	160	142			
2.25	157	155	147			189
2.43	158	158	140			183
2.62	158	155	135			178
2.81	155	155	137			189
3.01	160	150	150			
3.22	155	155	140			190
3.44	155	158	140			184
3.66	157	161	126			178
3.89	158	161	137			180
4.12	157	158	137			183
4.36	158	161	140			187
4.61	155	147	144		191	191
4.86	155	155	137			183
5.11	147	150	137	192		184
5.36	155	155	142			190
5.62	161	150	140			186
5.87	155	161	147			189
6.13	155	163	130			180
6.38	161	155	140			186
6.63	155	155	144			
6.88	166	150	140			180
7.13	155	155	135			183
7.36	155	155	140			187
7.60	150	155	140			189
7.82	158	161	140			191
8.03	161	147	137			187
8.24	161	155	137			191
8.43	155	155	135			177
8.60	147	155	137	190		187
8.77	150	150	140	191		182
8.91	150	161	137			184
9.04	147	147	126			172
9.14	161	157	140			184
9.23	150	155	126			176
9.29	150	147	135	192	190	179
9.32	147	150	126	187		173
9.33	155	150	135			181
9.31	150	142	135	189		183

Lisianthus Forever	Days to visible bud			Days to flower		
PPFD ($\mu mol/m^2/s$)	CF DE	CF NB	T NB	CF DE	CF NB	T NB
SD		159			>193	
0.30	155	147	155			
0.39	155	142	147			
0.49	155	144	140			184
0.60	155	142	142			
0.73	150	150	126	190		176
0.87	155	147	126			176
1.04	150	147	126			176
1.24	150	144	128			180
1.46	155	147	126			169
1.71	147	140	150	186	181	
1.99	155	147	121			169
2.29	150	137	137	190	184	184
2.63	155	147	126			174
2.99		147	121			174
3.38	140	142	126	184	185	171
3.79	155					
4.22	150	137	126		188	206
4.67	150	150	130			176
5.13	147	150	140	190		187
5.60	147	144	135		190	186
6.07	155	147	119			171
6.54	155	155	130			176
6.99	155	150	123			169
7.43	150	147	137			184
7.85	150	147	126			171
8.23	150	150	121			164
8.57	137	130	126	181	178	173
8.86	150	150	135			176
9.09	150	155	135	191		187
9.25	155	147	126			171
9.32	155	147	116			162
9.31	142	150	123	185		173

Pansy	Days to visible bud			Days to flower		
PPFD (μmol/m^2/s)	CF DE	CF NB	T NB	CF DE	CF NB	T NB
SD	56.7			82.8		
0.30		59	56		89	73
0.35		58	51		83	67
0.40	59	59	59	83	83	93
0.45		52	52		70	78
0.51		52	51		71	65
0.57		57	57		80	80
0.63	54	58	44	77	82	60
0.70	58	52	44	94	72	58
0.77	55	57	49	94	84	64
0.86	52	49	52	73	63	70
0.94	58	59	46	82	81	63
1.04		54	53		71	73
1.14		64	44		82	61
1.25	54	57	49	73	77	66
1.37		54	46		75	62
1.50	55	58	49	84	80	63
1.63	59	44	49	92	62	65
1.77	58	49	46	80	62	64
1.93	57	58	53	80	81	71
2.09	58	54	51	84	73	67
2.25	64	58	51	85	80	68
2.43	42	58	49	62	87	61
2.62	58	51	44	78	69	56
2.81	59	55	49	98	77	63
3.01	55	54	44	85	72	56
3.22		57	44		77	55
3.44	50	51	39	68	63	51
3.66	62	49	51	78	61	67
3.89	54	58	49	74	80	64
4.12	59	46	46	78	63	60
4.36	55	52	46	74	70	61
4.61	55	52	51	78	70	67
4.86	49	46	39	65	57	54
5.11	49	46	42	61	61	55
5.36	54	55	52	77	78	69
5.62		53	42		71	58
5.87	49	59	42	65	82	56
6.13		49	46		63	60
6.38	49	58	44	67	78	56
6.63	51	44	51	68	58	65
6.88		53	44		68	59
7.13	58	54	44	79	73	55
7.36	58	59	39	80	82	50
7.60	52	55	39	73	77	50
7.82		49	54		64	69
8.03	59	51	49	83	68	66
8.24		46	51		59	70
8.43	63	55	44	80	74	57
8.60	58	52	44	75	70	58
8.77	58	54	42	84	70	54
8.91	57	52	42	74	68	54
9.04		59	39		80	51
9.14		49	51		63	67
9.23		39	44		53	55
9.29		54	46		71	62
9.32		51	49		67	62
9.33		52	39		65	51
9.31	63	54	46	100	71	60

Petunia	Days to visible bud			Days to flower		
PPFD ($\mu mol/m^2/s$)	**CF DE**	**CF NB**	**T NB**	**CF DE**	**CF NB**	**T NB**
SD	92.7			106.3		
0.30	63	62	59	76	73	71
0.35	63	61	59	76	74	70
0.40	63	63	59	76	76	70
0.45	65	63	61	79	78	71
0.51	65	59	60	79	72	72
0.57	63	65	56	76	76	70
0.63	63	63	61	76	78	74
0.70	63	62	56	77	76	69
0.77	65	61	60	79	73	72
0.86	63	63	59	73	77	72
0.94	63	58	54	76	69	65
1.04	61	59	55	73	71	66
1.14	63	59	56	76	71	70
1.25	62	62	56	75	73	69
1.37	61	63	56	72	76	68
1.50	62	61	54	78	74	65
1.63	61	58	53	73	69	63
1.77	63	58	55	76	70	65
1.93	62	60	54	76	70	66
2.09	61	59	53	74	73	65
2.25	61	56	56	76	67	67
2.43	56	59	53	69	69	64
2.62	62	62	54	76	74	66
2.81	61	62	54	76	73	66
3.01	59	62	54	71	74	66
3.22	61	58	51	75	69	62
3.44	64	63	53	76	76	62
3.66	56	61	51	69	74	65
3.89	62	64	55	76	76	67
4.12	61	59	54	74	70	66
4.36	61	63	54	73	76	65
4.61	59	59	55	72	69	65
4.86	56	62	51	67	74	64
5.11	59	65	51	70	77	63
5.36	58	59	51	69	69	64
5.62	59	61	51	72	73	63
5.87	58	58	53	72	70	64
6.13	58	61	49	70	74	62
6.38	58	61	49	69	71	62
6.63	51	59	51	64	70	63
6.88	54	60	51	65	73	64
7.13	61	60	54	75	73	66
7.36	54	58	52	66	67	65
7.60	59	62	49	72	74	62
7.82	58	61	51	71	73	66
8.03	59	51	51	70	63	62
8.24	56	58	51	69	69	62
8.43	56	58	46	68	69	61
8.60	53	57	49	64	68	61
8.77	56	65	46	66	88	61
8.91	58	56	49	69	69	60
9.04	54	59	49	66	71	61
9.14	54	59	51	67	72	63
9.23	53	58	51	64	69	62
9.29	54	57	46	64	68	61
9.32	56	51	49	65	62	60
9.33	54	58	51	65	69	62
9.31	50	62	49	63	76	60

Poinsettia	Days to red bract			Days to cyathia		
PPFD (μmol/m^2/s)	CF DE	CF NB	T NB	CF DE	CF NB	T NB
SD	41.3			87.5		
0.30	69	158	94	116		145
0.39	64	149	67	116		106
0.49	102		53	158		106
0.60	76	85		113		
0.73	69			113		
0.87	81		76	181		
1.04		179				
1.24	71			120		
1.46	71		88	116		
1.71	83	145	83	145		
1.99	69		64	116		145
2.29	67			106		
2.63	69		97			
2.99	81		97	158		
3.38	76			148		
3.79	76			123		
4.22	81		97	123		
4.67	52			120		
5.13	74	97		123	118	
5.60						
6.07	48			151		
6.54	62			165		
6.99	81			116		
7.43	67			113		
7.85	76	179	85	113		
8.23	83			151		
8.57	69			132		
8.86	67	69		151		
9.09	67			145		
9.25	81	76	181	176		
9.31			127			
9.32	83					

