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Low-intensity blue light in night-interruption lighting does not influence flowering of herbaceous ornamentals

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ABSTRACT

The spectral quality of photoperiodic lighting can affect flowering of short-day plants (SDPs) and long-day plants (LDPs) differently. When delivered during the middle of the night (night interruption, NI), red (R; 600–700 nm) light alone can inhibit flowering of SDPs, whereas a combination of R and far-red (FR; 700–800 nm) light promotes flowering of some LDPs. However, whether or not low-intensity (≈1–2 μmol m^{-2} s^{-1}) blue (B; 400–500 nm) light, when added to R and/or FR light, influences flowering has not been established. We investigated the effects of mixed B, R, and FR light on flowering of five SDPs [chrysanthemum (*Chrysanthemum* × *morifolium*), cosmos (*Cosmos sulfureus*), two cultivars of dahlia (*Dahlia pinnata*), and marigold (*Tagetes erecta*)] and two LDPs [dianthus (*Dianthus chinensis*) and rudbeckia (*Rudbeckia hirta*)]. Plants were grown in a greenhouse at a constant set point of 20 °C and received a truncated 9-h short day (SD) with or without 4-h NI lighting from incandescent (INC) lamps or white (W), B, B + R, B + FR, B + R + FR, or R + FR light-emitting diodes (LEDs). Each NI lighting treatment delivered a mean photon flux of 1.5 μmol m^{-2} s^{-1} between 400 and 800 nm at plant height. Blue light alone was not perceived as a long day by all SDPs and LDPs tested. For all SDPs, W LEDs inhibited flowering most effectively. B + R NI was as effective as W NI at creating a long day for all SDPs except chrysanthemum. B + FR NI inhibited flowering of marigold and dahlia 'Leanne', but not chrysanthemum or dahlia 'Gallery Pablo'. For marigold, B + FR NI was less effective than other NI lighting treatments with R light. B + R + FR and R + FR NI similarly delayed flowering of all SDPs except dahlia 'Gallery Pablo'. NI lighting treatments containing R light similarly promoted flowering of rudbeckia. We conclude that in at least the crops studied, low-intensity B light during the night does not influence flowering. In addition, W LEDs that emit little FR light are effective at creating long days for SDPs but only some LDPs.

1. Introduction

Flowering is influenced by various internal and external factors, including developmental competence, circadian rhythms, photoperiod, and vernalization (Hayama et al., 2007; Lee and Amasino, 1995; Thomas and Vince-Prue, 1997). Many different responses, such as flowering, dormancy, and tuberization, are controlled by photoperiod in a wide range of plants (Jackson, 2009). Seasonal changes in daylength can be sensed by plants to regulate the flowering process. With respect to flower initiation in response to daylength, most plants can be categorized into SDPs, LDPs, and day-neutral plants (Thomas and Vince-Prue, 1997). Flowering of SDPs and LDPs is induced when the skotoperiod is longer or shorter than some critical duration, respectively. When the natural daylength is short, electric lighting delivered as NI lighting can inhibit flowering of SDPs and promote flowering of LDPs. NI light intensity of 1–2 μmol m^{-2} s^{-1} from broad-spectrum conventional light sources is typically sufficient to regulate flowering (Whitman et al., 1998).

Phytochrome, a primarily R and FR light-absorbing photoreceptor, and cryptochrome, a primarily B and ultraviolet-A light-absorbing photoreceptor, are involved in regulation of flowering (Cashmore et al., 1999). Depending on species, multiple phytochromes (phyA, phyB, phyC, phyD, and phyE) and cryptochromes (cry1 and cry2) can exist (Clack et al., 1994; Sharrock and Quail, 1989). In at least some species in the Brassicaceae family, phytochromes and cryptochromes can interact and overlap in function (Cashmore et al., 1999). The R/FR reversibility refers to the paradigm that phytochrome-mediated responses, such as flowering and seed germination, can be at least partially reversed by converting phytochromes between their inactive R light-absorbing form, P_R, and active FR light-absorbing form, P_{FR}. Irradiance and

Abbreviations: B, blue; FR, far red; INC, incandescent; LDP, long-day plant; LED, light-emitting diode; NI, night interruption; *PPF*, photosynthetic photon flux; R, red; SD, short day; SDP, short-day plant; VB, visible flower bud or inflorescence; W, white.

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the R to FR light ratio (R:FR) elicit formation of P_R and P_{FR}, the proportions of which determine an estimated phytochrome photoequilibrium (P_{FR}/P_{R+FR}) (Sager et al., 1988).

The effectiveness of spectral wavebands in NI lighting to control flowering is somewhat different for SDPs and LDPs. In SDPs, R light is the most effective waveband to inhibit flowering (Thomas and Vince-Prue, 1997). The effect can be at least somewhat reversed by subsequent exposure to FR light, indicating involvement of phytochromes. A particular intensity threshold is required for specific wavelengths to interrupt the night effectively. For example, monochromatic light of 450, 550, 650, or 750 nm inhibited flowering of the SDP duckweed (*Lemna paucicostata*), but the light intensity required for 50% flowering inhibition was 10, 0.5, 0.1, and 3 $\mu mol\ m^{-2}\ s^{-1}$, respectively (Saji et al., 1982). In some LDPs such as *Arabidopsis*, R light was effective at promoting flowering, but B and FR light were both more effective than R light at a similar intensity of 0.8–1.0 $\mu mol\ m^{-2}\ s^{-1}$ (Goto et al., 1991). However, B light at 3.3 $\mu mol\ m^{-2}\ s^{-1}$ and FR light at 1.3–1.6 $\mu mol\ m^{-2}\ s^{-1}$ were not perceived as a long day for a variety of photoperiodic ornamental crops (Craig, 2012; Craig and Runkle, 2012). Therefore, the efficacy of one or more wavebands of light at regulating flowering varies among species. Different combinations of wavebands can be more effective than monochromatic light. For example, a mixture of R and FR light was more effective at promoting flowering of LDPs than either alone (Craig and Runkle, 2012; Thomas and Vince-Prue, 1997).

LEDs emitting similar intensities of R and FR light effectively regulated flowering of both SDPs and LDPs (Craig and Runkle, 2012, 2013). However, the effects of additional B light to R and/or FR light in NI lighting have been inconclusive. For example, flowering was earlier in chrysanthemum 'Huang-Hsiu-Feng' and later in chrysanthemum 'Lung-Feng-Tzu' under a B + R (B:R = 1:3) NI than an R NI (Ho et al., 2012a). Moreover, a combination of B and R light (B:R = 1:1) promoted flowering of the LDP cyclamen (*Cyclamen persicum*) more effectively than B, R, or FR light alone (Shin et al., 2010). However, B + R (B:R = 1:1) NI and R NI were similarly effective at inhibiting flowering of chrysanthemum (Ho et al., 2012b). The objective of this study was to investigate the effects of NI lighting from different combinations of B, R, and/or FR light provided by LEDs on flowering characteristics of a variety of daylength-sensitive ornamental crops. We postulated that low-intensity B light would have no effect on flowering when added to R and FR light for NI lighting. In addition, we anticipated that W LED lamps would be less effective than INC lamps for some crops because W LED lamps emit little FR light.

2. Materials and methods

2.1. Plant material

The experiment utilized a randomized complete block design with time as a block. Photoperiod treatments were alternated randomly between blocks. The experiment was performed twice, with the same growing practices and similar greenhouse environmental conditions. The experiment was first performed from 25 Jan. to 25 May 2013 and was replicated from 9 Apr. to 14 Oct. 2013. The plant species examined included five SDPs: chrysanthemum 'Golden Cheryl', cosmos 'Cosmic Yellow', dahlia 'Leanne' and 'Gallery Pablo', and marigold 'American Antigua Yellow'; and two LDPs: dianthus 'Super Parfait Raspberry' and rudbeckia 'Indian Summer'. Rooted cuttings of dahlia 'Leanne' and 'Gallery Pablo' were received from a commercial grower (Bosgraaf Greenhouses, Inc., Hudsonville, MI) on 15 Jan. 2013 and 8 Apr. 2013. Plugs of all the other young plants, grown from either seed or cuttings by a commercial young-plant producer (C. Raker & Sons, Inc., Litchfield, MI), were received on 15 Jan. 2013 for the first replication, within one week of seed sow, or after liners were rooted. For the second replication, most young plants were received on 25 Apr. 2013, whereas rooted cuttings of chrysanthemum were received on 10 May 2013. To avoid flower induction, all SDPs were grown under a 16-h photoperiod (consisting of natural days supplemented with light from high-pressure sodium lamps), and all LDPs were grown under a truncated 9-h SD photoperiod at a constant set point of 20 °C in a research greenhouse until the start of treatments. Once the plants were ready for transplant, 10 randomly selected plants per treatment and cultivar were potted with a commercial peat-perlite medium (Suremix; Michigan Grower Products, Inc., Galesburg, MI) and transferred to different treatments in another research greenhouse maintained at a constant set point of 20 °C. Chrysanthemum, cosmos, dahlia (both cultivars), and marigold were transplanted on 7 Feb., 24 Jan., 24 Jan., and 24 Jan. 2013, respectively, for the first replication, and on 10 May, 2 May, 9 Apr., and 2 May 2013, respectively, for the second replication. Dianthus and rudbeckia were transplanted on 6 Feb. and 7 Feb. 2013, respectively, for the first replication, and on 2 May and 8 May 2013, respectively, for the second replication.

2.2. Lighting treatments

A truncated 9-h natural SD photoperiod was achieved by closing opaque black cloth at 17:00 h and opening it at 08:00 h for all treatments. In addition to a 9-h SD control, 4-h NI lighting treatments were delivered from 22:30 to 02:30 h by INC lamps (60 W; Philips, Amsterdam, Netherlands) or W (10.5 W; peak wavelength = 606 nm; model 9290002204; Philips Lighting, Somerset, NJ), B (18 W; peak wavelength = 462 nm; model 121109-125040-7779; LEDwholesalers, Hayward, CA), B + R (peak wavelength = 659 nm), B + FR (peak wavelength = 737 nm), B + R + FR, or R + FR LEDs. R and FR light were delivered by customized LED fixtures containing three R and/or FR LEDs per fixture (5 W; CCS, Inc., Kyoto, Japan). The mean photon flux at plant height was calculated from measurements at four different locations within the treatment area with a portable spectroradiometer (PS200; StellarNet, Inc., Tampa, FL) and was adjusted to 1.3–1.7 $\mu mol\ m^{-2}\ s^{-1}$ between 400 and 800 nm for all NI lighting treatments by lamp positioning and use of aluminum mesh. Spectral distribution characteristics of NI lighting treatments are provided in Table 1 and Fig. 1. Plants were placed on the bench area only where light intensity at plant height was between 1 and 3 $\mu mol\ m^{-2}\ s^{-1}$. The NI lighting treatments using multiple combinations of LEDs delivered equal intensities of different colors. For each NI lighting treatment, the R:FR was calculated with 10- and 100-nm wavebands, and the phytochrome photoequilibrium was estimated with the spectra in Fig. 1, as described by Sager et al. (1988).

2.3. Greenhouse environment

The experiment was conducted in a glass-glazed greenhouse at Michigan State University (East Lansing, MI) maintained at a constant air temperature set point of 20 °C as controlled by a greenhouse environmental control system (Integro 725; Priva North America, Vineland, ON, Canada). Roof and side vents, cellulose evaporative-cooling pads, and exhaust fans in the greenhouse were used for ventilation and cooling when needed. In addition, whitewash was applied externally on the greenhouse glass during the second replication to reduce solar heating in the greenhouse. An aspirated thermocouple [36-gauge (0.127-mm diameter) type E] located in the middle of each bench measured air temperature at plant height every 10 s, and a data logger (CR10; Campbell Scientific, Logan, UT) recorded hourly means. The data logger controlled a 1500-W electric heater underneath each bench to automatically