Effect of Light Quality on Developmental Rate of Wheat under Continuous Light at a Constant Temperature

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Abstract: The developmental rate of wheat was investigated under continuous light of eight different qualities (in eight plots) obtained by combining three out of four different kinds of fluorescent lamps (white, blue, purplish red and ultraviolet-A) at a constant temperature of 20°C. A Japanese spring wheat var. Norin 61 and a winter wheat var. Shun-yo were used. The number of days from seeding to heading varied extensively with the variety and the light quality. The first heading was observed in the plot under three white fluorescent lamps (W + W + W) at 37 and 81 days after seeding in Norin 61 and Shun-yo, respectively. The developmental rate in both cultivars was significantly correlated with the ratio of energy in 500–550 nm range (green light) and 600–700 nm range (red light) to that in the whole spectral range (250–1,000 nm). These results suggest that green and red lights play important roles in the regulation of the developmental rate independent of photoperiodism and vernalization.

Key words: Developmental rate, Green light, Heading time, Light quality, Red light, Wheat.

Wheat (Triticum aestivum L.) includes many species that can cross with related species, e.g., Aegilops, Secale and Haynaldia (Harlan, 1992). The genome size of wheat is very large as compared with rice and maize (Bennett and Leitch, 1995). Therefore, crossing has played an important role in the evolution of wheat and may continue to do so in gene recombination in the future. From this viewpoint, the regulation of developmental rate of wheat is essential for crossing among different species and strains in the breeding program. In general, acceleration of heading shortens the generation cycle and improves the efficiency of the crossing. However, it is difficult to change drastically the heading time of wheat, as the mechanism of flowering is not yet fully known. The developmental rate shown by the time of heading is usually affected by photoperiod and vernalization (Miralles and Slafer, 1999). Recently, studies on the mechanism of photoperiodism and vernalization have made great advances in Arabidopsis (Levy and Dean, 1998; Simpson and Dean, 2002). The circadian clock is involved in the photoperiodic control of flowering (Samach and Coupland, 2000).

On the other hand, flowering is also affected by the light quality mainly by the action of phytochromes (Vince-Prue, 1983; Fitter and Hay, 2002). In general, the spectral quality influences photomorphogenic responses such as germination and phototropism. For instance, blue light plays an important role in regulation of floral initiation and morphology in Arabidopsis (Eskins, 1992). The flowering time of Cyclamen persicum M. can be controlled by manipulating light quality and photoperiod (Heo et al., 2005). The effect of light quality on growth and morphology of wheat has been studied (Barnes and Bugbee, 1992; Goins et al., 1997). However, few reports show the influence of light quality on heading time in wheat.

Materials and Methods

1. Plant material and experimental conditions

An indoor experiment was conducted using two Japanese commercial varieties, spring wheat “Norin 61” that belongs to class II (Gotoh, 1979) in the degree of winter habit and winter wheat “Shun-yo” that belongs to class IV (Ushiyama et al., 1998).
seeds were sown and the seedlings grown on garden soil in plastic pots (45 × 45 × 50 mm), one plant per pot. The seedlings were then grown under continuous light with different qualities in a room maintained at 20°C, to eliminate the effects of photoperiod and vernalization. Eighteen plants of each variety were used per treatment in a completely randomized design with two replications.

2. Combination of different types of fluorescent lamps

Three of the four types of fluorescent lamps (white, blue, purplish red and ultraviolet-A) were combined to produce eight kinds of light (L1-L8) with different light qualities (Fig. 1 and Table 1). After emergence, the seedlings were exposed continuously to L1-L8. The light from UVA lamps was given for 15 minutes at two-hour intervals to eliminate injury by the ultraviolet light.

3. Measurement of spectral distribution and heading time

The spectral distributions of the light in L1 to L8 plots were measured with a spectroradiometer, HSU-100S (Asahi Spectra Co. Ltd., Japan) on the dimension of $\mu$W cm$^{-2}$ nm$^{-1}$. Table 1 shows the ratio of the energy in the restricted spectral range (UVA, B, G, R, and FR) to that in the measurable whole spectral range (250-1,000 nm), and photosynthetic photon flux density in each plot (L1 –L8). Heading was recorded every day after the first heading in each plot. We analyzed the relationship between light quality and the developmental rate as will be described later.

Results

1. Heading time in each plot with different light qualities

The number of days to the first heading and to 50% heading in each plot was shorter in the plots without UVA (L1-L4) than in the plots with UVA (L5-L8) in both varieties (Table 2). In both varieties, the first heading was the earliest in the L1 plot (W + W + W, white light) and it was 37 and 81 days after seeding in Norin 61 and Shun-yo, respectively. In both varieties, the day of 50% heading was the earliest in the L1 and L2 (W + PR + PR) plots. The number of days to 50% heading (Table 2) significantly correlated with PPFD.

![Energy density vs. wavelength](image)

Fig. 1. The emission spectra of four kinds of fluorescent lamps used in the experiment.

W = White (Mellow White, 15W, Toshiba Co. Ltd., Japan), PR = Purplish red (Exotic Rose, 15W, Sudo Co. Ltd., Japan), B = Blue (Caribbean Blue, 15W, Sudo Co. Ltd., Japan), UVA = Ultraviolet-A, (Black light, 15W, Funakoshi Co. Ltd., Japan).

Table 1. The quality and quantity of light in experimental plots (L1-L8).

| Plot | Combination of lamps$^3$ | RE in each spectral region$^5$ | PPFD$^6$ (µmol m$^{-2}$ s$^{-1}$) |
|------|--------------------------|---------------------------------|----------------------------------|
|      |                          | UVA   | B     | G     | R     | FR    |                                  |
| L1   | W + W + W               | 0.026 | 0.302 | 0.437 | 0.187 | 0.026 | 355                              |
| L2   | W + PR + PR             | 0.016 | 0.444 | 0.260 | 0.243 | 0.021 | 388                              |
| L3   | W + B + B               | 0.006 | 0.784 | 0.175 | 0.021 | 0.007 | 431                              |
| L4   | W + PR + B              | 0.013 | 0.559 | 0.240 | 0.158 | 0.017 | 388                              |
| L5   | W + UVA + W             | 0.367 | 0.218 | 0.259 | 0.102 | 0.019 | 242                              |
| L6   | W + UVA + PR            | 0.319 | 0.284 | 0.212 | 0.139 | 0.017 | 242                              |
| L7   | W + UVA + B             | 0.402 | 0.270 | 0.209 | 0.074 | 0.015 | 214                              |
| L8   | PR + UVA + B            | 0.455 | 0.367 | 0.102 | 0.034 | 0.010 | 205                              |

$^3$ See Fig. 1.

$^5$ Ratio of energy in UVA (320-400 nm), B (400-500 nm), G (500-600 nm), R (600-700 nm) and FR (700-800 nm) range to that in whole spectral range (250-1,000 nm).

$^6$ Photosynthetic photon flux density was obtained by integrating energy of light between 400 and 700 nm. The density was measured on leaf top at the mid stage between germination and heading stage.
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(Table 1) in Norin 61 (r = −0.808, p < 0.05), but not in Shun-yo (r = −0.290).

2. Relationship between the light quality and the number of days to heading

The correlation between the number of days to 50% heading in each plot and light quality in respective plots was examined. We calculated the reciprocal number of the days to 50% heading and analyzed this value as the developmental rate. In addition, we calculated the ratio of light energy in the specified wavelength range (50 nm width) to that in the whole spectral range (250–1,000 nm), which is referred to as RE in a specified wavelength range in this paper. Fig. 2 shows the correlation coefficient (ordinate) between developmental rate in each plot and RE in various spectral ranges (abscissa) in respective plots. A significant positive correlation was observed in the 500–550 nm (green light) and 600–700 nm ranges (red light). However, no significant correlation was observed in the 400–500 nm range (blue light) in both varieties, and a negative correlation in 300–400 nm range (ultraviolet) in Norin 61. Fig. 3 shows the correlation of developmental rate in each plot with RE in the 600–700 nm (red) and 500–550 nm (green) ranges in respective plots. The developmental rate significantly correlated with RE in red and green ranges at p < 0.01 level in Norin 61 and at p < 0.05 level in Shun-yo.

Discussion

The developmental rate of wheat varied extensively with the light quality under continuous light at a constant temperature. This experiment revealed that the heading time was affected by light quality, independent of photoperiod and vernalization (Table 2). Early study (Funke, 1948) showed that flowering of long-day plants other than Cruciferae was promoted by red or white light, and that of short-day plants and Cruciferae was promoted by blue light. An action spectrum for floral promotion of wheat by daylight extension, with action maxima at 660 nm and 716 nm, was obtained (Carr-Smith et al., 1989). In the present study, developmental rate of wheat positively correlated

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Table 2. Days to heading in each plot.

| Plot | Combination of lamps | Days to first heading | Days to 50% heading |
|------|----------------------|-----------------------|---------------------|
|      |                      | Norin 61/ Shun-yo      | Norin 61/ Shun-yo    |
| L1   | W + W + W            | 37/ 81                 | 42/ 133             |
| L2   | W + PR + PR          | 38/ 90                 | 41/ 134             |
| L3   | W + B + B            | 43/ 103                | 48/ 151             |
| L4   | W + PR + B           | 41/ 122                | 45/ 151             |
| L5   | W + UVA + W          | 44/ 152                | 51/ 152             |
| L6   | W + UVA + PR         | 44/ 100                | 52/ 139             |
| L7   | W + UVA + B          | 49/ 127                | 57/ 149             |
| L8   | PR + UVA + B         | 47/ 123                | 53/ 154             |

LSD<sup>4)</sup> <br>3.1 12.8 4.1 5.3

<sup>1)</sup> See Fig. 1.  
<sup>2)</sup> Number of days from seeding to first heading and <sup>3)</sup> 50% heading, which were determined from regression lines of the percentage of heading plants plotted against days after seeding.  
<sup>4)</sup> LSD shows significant level at p < 0.01.
Effect of Light Quality on Development with RE in 600–700 nm range, suggesting a promoting effect of red light on wheat heading.

In the present experiment, RE in the green light range significantly affected the developmental rate of wheat in addition to RE in red light range. In general, green light largely reflects or passes through the plant canopy. Thus, under the plant canopy, proportions of blue and red light are decreased; those of green and far-red light are increased (Smith, 1982; Kasajima et al., 2006). These changes in light quality under the canopy cause a decrease of R/FR (the ratio of red to far-red), thereby accelerating the flowering time (Halliday et al., 1994; Ballare, 1999). Thus, the inferior individuals located under the canopy may head in response to green light in order to coincide with the heading of superior individuals in the canopy that effectively absorbed red and blue lights. The plant’s response to green light may be important in understanding the ecological significance of green light.

In Arabidopsis, blue light plays an important role in regulation of floral initiation (Eskins, 1992; Goins et al., 1998). However, in the present experiment, no correlation was observed between developmental rate and RE in the 400–500 nm range (blue light). This result suggests that the effect of light quality on flowering varies with the plant species.

Thus, light quality appears to be important in the regulation of the developmental rate as well as photoperiod and vernalization. In general, clouds and aerosol in atmospheric air influence the quality of solar radiation on the surface of the earth. The direct radiation and duration of sunshine are usually reduced.

Fig. 3. Correlation of developmental rate in each plot (L1–L8) with RE in 600–700 nm (red light) and 500–550 nm (green light) ranges.

(a), (c) = Norin 61, (b), (d) = Shun-yo.
For developmental rate and RE see legend for Fig. 2.
on cloudy days (Seino, 1987), and thick clouds usually reduce ultraviolet radiation in comparison with a clear day (Xenopoulos and Schindler, 2001). The heading time of wheat may be delayed under the cloudy conditions because of the shortened day length. Conversely, RE in the 600-700 nm ranges may increase under the cloudy conditions because the amount of energy in shorter wavelengths is decreased by the dispersion and reflection of sunshine in the clouds. Thus, the heading time of wheat on cloudy days is expected to be enhanced by a high ratio of red light. This type of response to light quality may have a compensatory effect in stabilizing the heading time of wheat under natural meteorological conditions with daily fluctuations.

In the present study, the experiment was conducted under continuous light at a constant temperature to eliminate the effects of photoperiod and vernalization. In Arabidopsis, there were five types of flowering, regulated by photoperiod, autonomous process, vernalization, gibberellin and light quality (Ausín et al., 2005). In addition, the regulation of flowering in Arabidopsis by phytochrome B in a photoperiod-independent pathway has been reported (Gerdan and Chory, 2003). In the present experimental condition, the function of light quality for regulation of developmental rate appeared to be independent of photoperiod and vernalization. This result may support the existence of a metabolic pathway in relation to light quality.

The effects of light quality on the developmental rate were similar in both spring and winter varieties, but there was a difference between the two varieties. There was a significant correlation between the PPFD (Table 1) and the number of days to 50% heading (Table 2) in Norin 61, but there was no correlation in Shun-yo. In addition, there was a close negative correlation between the RE in UVA range and the developmental rate in Norin 61, but there was no correlation in Shun-yo (Fig. 2). These results indicate that the amount of assimilate may affect the days to heading in Norin 61, but not in Shun-yo. This difference between the varieties may be attributed to the difference of growth rate. Namely, the number of days to heading was shorter about three times in Norin 61 than in Shun-yo (Table 2). This result indicates that dry matter production per day is higher in Norin 61 than in Shun-yo, which suggests that PPFD in L5-L8 (Table 2) is enough to satisfy the dry matter production per day in Shun-yo, but not in Norin 61. Therefore, the close negative correlation coefficient in Norin 61 in Fig. 2 may not be caused by UVA directly, but by PPFD indirectly. However, further studies with different varieties are necessary in the varietal difference.

In conclusion, light quality influences the developmental rate of wheat even under continuous light at a constant temperature. In addition, green and red lights may play an important role in regulation of the developmental rate in wheat independent of photoperiod and vernalization. We will conduct further studies in relation to the influence of green and red light on acceleration of the developmental rate in wheat.

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References

Ausín, I., Alonso-Blanco, C. and Martínez-Zapater, J.-M. 2005. Environmental regulation of flowering. Int. J. Dev. Biol. 49 : 689-705.

Ballare, C.L. 1999. Keeping up with the neighbors : phytochrome sensing and other signaling mechanisms. Trends Plant Sci. 4 : 97-102.

Barnes, C. and Bugbee, B. 1992. Morphological responses of wheat to blue light. J. Plant Physiol. 139 : 339-342.

Bennett, M.D. and Leitch, I.J. 1995. Nuclear DNA amounts in angiosperms. Annals of Botany 76 : 113-176.

Carri-Smith, H.D., Johnson, C.B. and Thomas, B. 1989. Action spectrum for the effect of day-extensions on flowering and apex elongation in green, light-grown wheat (Triticum aestivum L.). Planta 179 : 428-432.

Cerdan, P.D. and Chory, J. 2003. Regulation of flowering time by light quality. Nature 423 : 881-885.

Eskins, K. 1992. Light-quality effects on Arabidopsis development. Red, blue, and far-red regulation of flowering and morphology. Physiol. Plant. 86 : 439-444.

Fitter, A.H. and Hay, R.K.M. 2002. Environmental Physiology of Plants. Academic Press, London. 42.

Funke, G.L. 1948. The photoperiodicity of flowering under short day with supplemental light of different wavelengths. Lotosa. 1 : 79-82.

Goins, G.D., Yorio, N.C., Sanwo, M.M. and Brown, C.S. 1997. Photomorphogenesis, photosynthesis, and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting. J. Exp. Bot. 51 : 1407-1413.

Goins, G.D., Yorio, N.C., Sanwo-Lewandowski, M.M. and Brown, C.S. 1998. Life cycle experiments with Arabidopsis grown under red light-emitting diodes (LED). Life Support and Biosphere Science 5 : 143-149.

Gotoh, T. 1979. Genetic studies on growth habit of some important spring wheat cultivars in Japan, with special reference to the identification of the spring genes involved. Japan. J. Breed. 29 : 133-145.

Halliday, K.J., Koornneef, M. and Whitelam, G.C. 1994. Phytochrome B and at least one other phytochrome mediate the accelerated flowering response of Arabidopsis thaliana L. to low red/far-red ratio. Plant Physiol. 104 : 1311-1315.

Harlan, J.R. 1992. Crops and Man. American Society of Agronomy, Wisconsin. p109.

Heo, J.W., Lee, C.W., Murthy, H.N. and Paek, K.Y. 2003. Influence of light quality and photoperiod on flowering of Cyclamen persicum Mill. cv. 'Dixie White'. Plant Growth
Regulation 40: 7-10.
Kasajima, S., Inoue, N., Fujita, K., Kato, M. and Kasuga, S. 2006. Vertical distribution of light spectra in the canopy of sorghum. Jpn. J. Crop Sci. 75 (Extra 1): 278-279*.
Levy, Y.Y. and Dean, C. 1998. Control of flowering time.Curr. Opin. Plant Biol. 1: 49-54.
Miralles, D.J. and Slafer, G.A. 1999. Wheat development. In E.H. Satorre and G.A. Slafer eds., Wheat: ecology and physiology of yield determination. Food Products Press, New York. 13-43.
Samach, A. and Coupland, G. 2000. Time measurement and the control of flowering in plants. BioEssays 22: 38-47.
Seino, H. 1987. Climatological calculus of solar energy. In K. Shibata and Z. Uchijima Eds., The Distribution and Measurement of Solar Energy. Japan Scientific Societies Press, Tokyo. 127-144**.
Simpson, G.G. and Dean, C. 2002. Arabidopsis, the rosetta stone of flowering time? Science 296: 285-289.
Smith, H. 1982. Light quality, photoperception, and plant strategy. Ann. Rev. Plant Physiol. 33: 481-518.
Ushiyama, T., Saito, M., Kubota, M., Kuwabara, T., Inokuchi, A., Tsuchiya, N., Hata, T., Kondo, T., Tanaka, M., Akanuma, R., Izumi, K. and Maejima, H. 1998. A new cultivar “Shun-yo”. Bull. Nagano Agr. Exp. Sta. Japan. 47: 53-61*.
Vince-Prue, D. 1983. Photomorphogenesis and flowering. In W. Jr. Shrophire and H. Mohr eds., Encyclopedia of Plant Physiology, New series. Springer-Verlag, Berlin. 457-490.
Xenopoulos, M.A. and Schindler, D.W. 2001. Physical factors determining ultraviolet radiation flux into ecosystems. In C.S. Cockell and A.R. Blausten Eds., Ecosystems, Evolution, and Ultraviolet Radiation, Springer, New York. 36-62.

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