Arabidopsis Response Regulators ARR3 and ARR4 Play Cytokinin-Independent Roles in the Control of Circadian Period

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INTRODUCTION

Most organisms on the planet live in a diurnal environment characterized by the succession of light and dark. To synchronize cellular, physiological, and behavioral processes to the appropriate time of day, they have developed complex signaling cascades whose role is to relay the information of light availability, quality, and quantity to the master circadian system. Of course, the information provided by the light/dark cycles does not drive the circadian oscillations seen in the daily life of an organism; rather, it entrains the clock—modulates the phase of the clock to synchronize the organism with its temporal environment. In Arabidopsis thaliana, phytochromes are among the photoreceptors that entrain the clock (Salomé and McClung, 2005b). Mutants lacking PHYTOCHROME B (phyB) in particular exhibit a lengthened period of LIGHT-HARVESTING CHLOROPHYLL a/b BINDING PROTEIN (LHCB) transcription under high fluences of red light (Somers et al., 1998) and cause a leading phase for a number of rhythms in white light (Hall et al., 2002; Salomé et al., 2002). Whether the leading phase seen in these plants is a result of a direct change in the phase of the clock is not known.

The circadian clock in Arabidopsis is formed by interconnected feedback loops between positive and negative elements. The two single Myb-domain transcription factors CIRCADIAN CLOCK-ASSOCIATED1 (CCA1) (Wang and Tobin, 1998) and LATE ELONGATED HYPOCOTYL (LHY) (Schaffer et al., 1998) act within the negative limb of the clock to repress the transcription of the positive factor, TIMING OF CAB EXPRESSION1 (TOC1, also known as PRR1) (Strayer et al., 2000). TOC1 and the Myb-like transcription factor LUX ARRHYTHMO are required for high expression of CCA1 and LHY, thereby closing the loop (Alabadi et al., 2001; Hazen et al., 2005). In addition, CCA1 and LHY play a positive role in the expression of the two TOC1-related genes PRR7 and PRR9 and may initiate a second loop critical for proper clock function and temperature entrainment (Farré et al., 2005; Nakamichi et al., 2005; Salomé and McClung, 2005a).

A model for light resetting of the Arabidopsis circadian clock was postulated to include phyB and the transcription factor PHYTOCHROME-INTERACTING FACTOR3 (PIF3) (Ni et al., 1998). PIF3 interacts strongly with the photoactivated far-red-absorbing form of phyB and to a weaker extent with phyA (Zhu et al., 2000). Because loss-of-function alleles in PIF3 lack any circadian mutant phenotype (Monte et al., 2004; Oda et al., 2004; Salomé and McClung, 2005b), the precise involvement of the transcription factor in light signaling to the clock is now in question. Quite possibly, the light-induced degradation of PIF3 by the proteasome may account for the lack of circadian defects, as the protein accumulates only in the dark (Bauer et al., 2004; Monte et al., 2004). Redundancy among family members may also obscure the exact role of PIF3 in light input to the clock (Bailey et al., 2003). Interestingly, a motif seen in the N terminus of some
PIFs and PILs was found to be critical for interaction with phytochromes and may provide a biochemical signature for basic helix-loop-helix proteins involved in light signaling (Khanna et al., 2004).

We have shown previously that mutations in phyB lead to a leading circadian phase after entrainment to light/dark cycles (Salomé et al., 2002). That the leading phase is not observed after entrainment to temperature cycles suggests that light input to the clock is affected. Besides PIF3, a number of potential sig intelliging intermediates in the phyB transduction pathway have been described. ARABIDOPSIS RESPONSE REGULATOR4 (ARR4) interacts with phyB in vitro and in vivo, and seedlings over-expressing ARR4 display a short hypocotyl consistent with the increased stability of and sustained signaling from the photo-receptor (Sweere et al., 2001). ARR4 belongs to the response regulator family, which has 23 members: 10 type-A regulators (including ARR4), 11 type-B regulators, and 2 others (Kakimoto, 2003). True response regulators are involved in signaling cascades in which an upstream cytokinin receptor kinase phosphorylates ARRs on a conserved Asp residue within their receiver domain (Schaller et al., 2002). Overexpression of type-A ARRs results in plants with reduced sensitivity to cytokinins, whereas overexpression of type-B ARRs leads to increased cytokinin sensitivity (Kiba et al., 2003; Tajima et al., 2004). Conversely, mutants lacking several type-A ARRs show an increased response to cytokinin, whereas mutants in type-B ARRs are more resistant to exogenous cytokinins (Kiba et al., 2003; To et al., 2004).

We set out to characterize the circadian behavior of many single, double, and higher order mutants containing T-DNA insertions into type-A ARRs. We show here that only the double mutant arr3,4 and the quadruple mutant arr3,4,5,6 display a long-period phenotype as well as a leading phase characteristic of phyB mutants, which is obscured by the long period seen in these mutants. The effect on the pace of the clock conferred by the loss of ARR3 and ARR4 is not attributable to a change in the sensitivity of the clock to cytokinins, as exogenous application of the hormone does not lengthen the period. Finally, we demonstrate a complex genetic interaction among type-A ARRs, as the phenotype conferred by arr3,4 can be completely suppressed by lesions in ARR8 and ARR9, although the arr8,9 double mutant has no circadian defect on its own. These findings represent an important step in the description of genes that are not essential

![Figure 1. Cotyledon Movement Survey of Type-A ARR Loss-of-Function Seedlings.](image_url)

Seedlings were grown under light/dark cycles (12 h of white light followed by 12 h of dark) for 5 d. On day 6, individual seedlings were transferred to 24-well plates and released into continuous white light. Cotyledon movement was recorded for 7 d and analyzed as described (Salomé and McClung, 2005a). The asterisk indicates a significant difference from Col (P < 0.001 as determined by one-way analysis of variance [ANOVA] and Duncan’s multiple comparison test).

(A) Mean period length of cotyledon movement for the wild type (Col) and type-A ARR loss-of-function alleles. Error bars represent 2 SE, from 12 to 24 seedlings.

(B) to (D) Average cotyledon movement traces for arr3 single (B), arr4 single (C), and arr3,4 double (D) mutants after entrainment by photocycles. Each trace represents the average from 12 to 24 individual cotyledons and is shown ± SE. Closed circles, mutant; open squares, Col; hatched bars, subjective night.
for the generation of rhythmicity but are critical for the proper regulation of the circadian parameters of period and phase, and they underscore the importance of characterizing whole gene families as opposed to limited sets of members.

RESULTS

Loss of the Type-A ARR3 and ARR4 Lengthens the Period of the Clock

We characterized the circadian parameters of single, double, and higher order T-DNA insertion mutants in type-A ARRs (To et al., 2004). Single or double loss-of-function mutations in most type-A ARRs did not affect the clock (Figures 1A to 1C). Among double mutant combinations between gene pairs with the highest similarity (ARR3 and ARR4, ARR5 and ARR6, ARR8 and ARR9), only the arr3,4 double mutant showed a striking long period (Figures 1A and 1D). No other double mutant analyzed shared this phenotype, nor did the arr3 and arr4 single mutants, indicating that the two genes redundantly contribute to the control of period length in cotyledon movement. Because this analysis considered only single alleles of each ARR gene, it remains possible that the long-period phenotype of the arr3,4 double mutant and of higher order combinations results from a third mutation introduced along with either arr3 or arr4. This hypothetical third mutation would have phenotypic consequence only in the arr3,4 double mutant, because neither single arr mutant has a long period. We analyzed F2 seedlings from a cross between arr3,4,5,6 and arr5,6 for segregation of a long period and observed the long period in one-sixteenth of the seedlings (data not shown), consistent with segregation of two genes and ruling out the possibility of an unlinked third mutation. However, we cannot exclude the possibility of a third, linked mutation by this analysis.

LUCIFERASE (LUC) fusions to the promoters of the clock genes CCA1, LHY, and TOC1 were introduced into the arr3 and arr4 single mutants, as well as the arr3,4 double mutant, to determine whether the two genes act upstream of the clock, in which case clock gene oscillations would be affected, or downstream as part of an output pathway controlling cotyledon movement, in which case clock gene expression would be unaltered. After the photocycles, the period of all three clock genes was lengthened in the arr3,4 double mutant, but it remained very close to normal in either single mutant (Figure 2). The same result was also seen after entrainment to warm/cold temperature cycles (thermocycles; data not shown), indicating that ARR3 and ARR4 likely act upstream of the clock and not along an output pathway.
pathway. Mean TOC1 period was lengthened slightly in the arr3 and arr4 single mutants, but the same was not true for mean CCA1 and LHY period. Therefore, ARR3 and ARR4 are largely redundant and perform an important role in the determination of circadian period in Arabidopsis.

Genetic Interaction among Type-A ARRs in the Control of Period Length

ARR3 and ARR4 belong to a minor clade within the type-A ARRs that includes ARR5, ARR6, ARR8, and ARR9 (To et al., 2004). Because these four additional genes may partially compensate for the loss of ARR3 and ARR4, we examined the circadian phenotypes of all quadruple mutants between gene pairs within the subclade, as well as the arr8,9 double mutant and the arr3,4,5,6,8,9 hextuple mutant. The arr5,6,8,9 quadruple mutant showed a wild-type period phenotype by cotyledon movement (Figure 3). Compared with the arr3,4 double mutant, no further period lengthening of cotyledon movement was observed in arr3,4,5,6 (Figure 3). Remarkably, period lengthening seen in the arr3,4 double mutant was completely suppressed by T-DNA insertion alleles of ARR8 and ARR9 in arr3,4,8,9 (Figure 3). The arr8,9 double mutant showed a normal period length by cotyledon movement, indicating that the loss of ARR8 and ARR9 is not itself sufficient to generate a circadian phenotype (Figure 3). The arr3,4,5,6,8,9 hextuple mutant similarly displayed no circadian phenotype (Figure 3B). A similar complexity in the genetic interactions between type-A ARRs was seen in petiole length and rosette size (To et al., 2004).

The arr8,9 double mutant suppressed the long period of the arr3,4 double mutant at the level of the expression of the clock genes themselves. Indeed, mean period lengths of the CCA1: LUC and LHY: LUC reporters were normal in arr8,9 and arr3,4,8,9, whereas the arr3,4,5,6 quadruple mutant period was long, similar to the period of arr3,4 (Figure 4).

Effects of Exogenous Cytokinin on the Expression of the Clock Genes

The expression of many type-A ARRs is induced in response to cytokinin (Kiba et al., 1999; D’Agostino et al., 2000). We wished to determine the effect of exogenous cytokinin treatment on the clock and so treated ecotype Columbia (Col) seedlings bearing a number of LUC fusions (LHCB, CCA1, CAT3, and TOC1) with increasing concentrations of kinetin, trans-zeatin, and benzyladenine (see Methods for details). Kinetin did not change period length but instead modified circadian phase in a dose-dependent manner (Figure 5A; see Supplemental Figure 1 online) for all LUC reporter constructs assayed. At low concentrations, kinetin resulted in a leading phase, whereas higher concentrations caused the phases of the reporters to lag behind those of untreated seedlings. That different hormone concentrations show type trace, whereas the peaks from arr3,4 and arr3,4,5,6 occur progressively later than Col, consistent with the long-period phenotype of these seedlings. Hatched bars, subjective night.
opposite effects is not uncommon; for instance, low levels of auxin promote root elongation, but higher concentrations repress the same process (Evans et al., 1994). Treating seedlings with various concentrations of trans-zeatin or benzyladenine caused the same effects as kinetin (data not shown). It is worth noting that high concentrations of cytokinins were applied, suggesting that their action on the clock may not be physiologically relevant. Lower concentrations had no effect (data not shown). Cytokinin sensitivity assays typically use levels as low as 100 nM, but many reports use this hormone in the 1 to 5 μM range to elicit a strong response, with 100 μM the highest level tested (Higuchi et al., 2004; Nishimura et al., 2004; To et al., 2004), so the leading phase seen at 5 μM kinetin may represent a true circadian response to the hormone. The amplitude of TOC1 expression was decreased at 50 and 100 μM kinetin (Figures 5C to 5F; see Supplemental Figure 1 online), which may suggest a toxic effect from the high kinetin levels.

We also tested the arr3 and arr4 single, arr3,4 double, and arr3,4,5,6 quadruple mutants under the same conditions and found that they responded to the hormone in a manner similar to...
Figure 5. Lagging Circadian Phase Caused by Exogenous Cytokinin Treatment in Col and Type-A ARR Mutants.

All seedlings were grown as described for Figure 2. On day 11, the cytokinin kinetin (solubilized in slightly acidic water) was added to each well at a final concentration of 5, 10, 50, or 100 μM. Plates were entrained for an additional 1 d in light/dark cycles before being released into continuous light. LUC activity was recorded for 6 d and analyzed as described in Methods. In all panels, data are shown ±SE from 12 to 24 seedlings.

(A) Mean sidereal phase values for the clock genes CCA1 and TOC1 and the clock-regulated genes LHCβ and CAT3 in the absence and presence of kinetin. Sidereal phase represents the time of the observed peak for a given rhythm, without normalization to the endogenous period length of the rhythm.

(B) to (E) Representative average traces for arr3 (B), arr4 (C), arr3,4 (D), and arr3,4,5,6 (E) in the absence (open squares) or presence (closed circles) of 100 μM kinetin.

(F) Mean sidereal phase for TOC1 expression in Col and arr3,4 in the absence and presence of increasing concentrations of kinetin.

(G) Mean sidereal phase for TOC1 expression in Col and arr3,4,5,6 in the absence and presence of increasing concentrations of kinetin.
wild-type seedlings, in addition to their circadian phenotype in the absence of treatment. Specifically, arr3,4 and arr3,4,5,6 displayed the long period characteristic of their observed phenotypes (Figures 1 and 3), but the phase of the rhythm was delayed relative to untreated mutant seedlings (Figures 5D to 5G) (To et al., 2004). If the long period seen in arr3,4 and arr3,4,5,6 is the result of an increased sensitivity to cytokinin, then exogenous treatment should phenocopy these mutants. Such is not the case, however, because cytokinin treatment does not lengthen period. This finding suggests that the long period observed in these mutants is not the consequence of altered cytokinin sensitivity. In support of this conclusion, arr3,4,5,6,8,9, which is the most cytokinin-sensitive mutant tested, exhibited a normal period (Figure 3).

Introduction of a genomic copy of ARR5 into arr3,4,5,6 can largely rescue the cytokinin insensitivity displayed by the quadruple mutant in the root elongation assay (To et al., 2004) but was not sufficient to eliminate the long period of the quadruple mutant (Figures 5H and 5I). In addition, ahk3,4 seedlings, lacking two of the three cytokinin receptors, showed no period or phase phenotype when assayed by cotyledon movement (Figure 5H), although they displayed very strong resistance to cytokinin treatment for callus formation (Nishimura et al., 2004).

Finally, analysis of available microarray data sets from the AtGenExpress database (http://Arabidopsis.org/servlets/TairObject?type=expression_set&id=1007966040) revealed that none of the clock genes are strongly affected by treatment with 1 µM trans-zeatin (Figure 5J) (Zimmermann et al., 2004). The type-A ARRs ARR4, ARR5, ARR6, and ARR7, on the other hand, showed very strong induction in response to the hormone, as expected (Figure 5J) (Kiba et al., 1999; D’Agostino et al., 2000). We conclude that cytokinins do not influence the expression of clock-regulated genes and therefore are unlikely to be responsible for the long-period phenotype seen in arr3,4 and arr3,4,5,6.

Loss of ARR3 and ARR4 Lengthens the Period of the Clock in All Conditions

The long-period phenotype of the arr3,4 and arr3,4,5,6 mutants is observed after either photocycles or thermocycles, indicating that ARR3 and ARR4 do not merely participate in a light input pathway leading to the clock. We wished to determine whether the period lengthening seen in arr3,4 and arr3,4,5,6 was dependent on the presence of light. We entrained seedlings to photocycles for 10 d and released the seedlings in constant red light or blue light or in constant darkness. As shown in Figure 6, all light conditions tested yielded a similar period lengthening of all genes tested in the arr3,4,5,6 mutant. The same was true for arr3,4 (data not shown). These findings demonstrate that ARR3 and ARR4 play an important role in the determination of circadian period and that their action is not mediated through modulation of a light input pathway.

ARR4 and ARR9 Expression Is Not under the Control of the Clock

The clock components CCA1, LHY, and TOC1, as well as the clock-associated genes PRR7 and PRR9, all show circadian control of their expression (Schaffer et al., 1998; Wang and Tobin, 1998; Matsushika et al., 2000; Strayer et al., 2000; Salomé and McClung, 2005a). ARR3 and ARR4 are expressed in all tissues (To et al., 2004), but it is unknown whether they might themselves be under clock regulation. Analysis of available microarray data sets from the Nottingham Arabidopsis Stock Centre (http://affymetrix.arabidopsis.info/narrays/experiment.page?id=108) indicated that ARR4 might be under clock regulation, with a peak in expression in the subjective evening, although with a very weak amplitude (Zimmermann et al., 2004). In that study, ARR3 levels were too low to accurately determine circadian regulation. We generated translational fusions by fusing ~2800 bp of the ARR4 promoter and ~2100 bp of the ARR9 promoter to the LUC reporter gene and introduced them into the Col ecotype by Agrobacterium tumefaciens-mediated transformation. At least 24 individual T1 seedlings were assayed for LUC activity; an average trace of these seedlings is shown in Figure 7A. TOC1:LUC data are given in Figure 7B as a reference for evening phase and amplitude expected from a known clock-regulated gene. ARR4:LUC showed a very weak oscillation in LUC activity, which coincided with peak expression of TOC1 (Figure 7C). However, our clock gene:LUC fusions exhibited a much stronger amplitude in their rhythm than did ARR4:LUC (cf. amplitudes from traces shown in Figures 7A and 7B; in Figure 7C, amplitudes have been adjusted). The weak amplitude in ARR4 expression may reflect some indirect effect, such as circadian variation in available ATP for LUC activity, rather than a true circadian regulation of ARR4 transcription. It remains to be determined whether ARR4 protein levels cycle or whether the activity of the protein is regulated in a circadian
manner. ARR4 protein accumulates in white and red light, and this was dependent on active phyB (Sweere et al., 2001). The expression of ARR9 did not appear to be under circadian control.

We conclude that the expression of ARR4 and ARR9, as seen with translational fusions to their respective promoters, is unlikely to be under strong circadian control.

**phyB-Like Phenotypes in arr3,4 and arr3,4,5,6 Mutants**

We initially set out to characterize mutants defective in the type-A ARRs for circadian defects to test the hypothesis that one or more would display a leading phase phenotype similar to that of phyB loss-of-function mutants. However, only a long period in the arr3,4 double and arr3,4,5,6 quadruple mutants was observed (Figures 1 to 4). Long-period mutants normally display a lagging phase phenotype during entraining cycles, and the phase of the rhythms during the first day in free-running conditions similarly lags behind that of the wild type (Pittendrigh, 1981; Dunlap et al., 2004; Salomé and McClung, 2005a).

The sidereal phase of the rhythm represents the time of the observed peak for a given rhythm, without normalization to the free-running period length of the rhythm. Sidereal phase values for Col, arr3,4, and arr3,4,5,6 were similar (Figures 8A and 8B), with arr3,4 showing a slightly lagging phase relative to Col, but not as pronounced as would be expected given the expected phase lag of 2 h (the free-running period of the mutant was 24 h for these entraining conditions). Therefore, the arr3,4 and arr3,4,5,6 mutants do not behave like typical long-period mutants and do not show the expected lagging phase. In fact, when sidereal phase values were converted to circadian time phase, arr3,4 and arr3,4,5,6 were seen to have a leading circadian time phase (Figure 8C), similar to the phenotype seen in phyB mutants (Salomé et al., 2002). These results suggest that ARR3 and ARR4 may modulate phyB signaling to the clock and that the loss of both ARR proteins can generate a leading phase in gene expression. However, the ability to detect this first effect on the clock (leading phase) is obscured by the second effect on the clock (long period).

Another phenotype characteristic of phyB mutants is their long hypocotyl in white light and red light (Somers et al., 1991; Salomé et al., 2002). Conflicting data exist on the precise role that ARR4 plays in this process. Overexpression of ARR4 shortens the hypocotyl in red light (Sweere et al., 2001), indicating a positive role in phyB signaling. However the arr3, arr4, and arr3,4 mutants also exhibit a shorter hypocotyl (To et al., 2004), suggesting a negative role for ARR3 and ARR4 in this signaling cascade. However, the range of fluences under which the hypocotyl phenotype is observed is distinct: low to high fluence but not very low fluence for ARR4-overexpressing plants, and very low to low fluence but not high fluence for arr3,4. While entraining our seedlings to photocycles, we noticed that arr3,4 and arr3,4,5,6 seedlings had long hypocotyls. Many mutants with circadian phenotypes show shorter or longer hypocotyls in shorter photo-periods but not in constant light (Doyle et al., 2002; Mizoguchi et al., 2002; Hall et al., 2003). When grown in short days, arr3,4 and arr3,4,5,6 plants have longer petioles than wild-type plants, and this phenotype is reminiscent of phyB mutants grown in the same conditions (To et al., 2004). We measured hypocotyl

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**Figure 6.** The Period of the Clock Gene LHY Is Lengthened in arr3,4,5,6 in All Light Conditions.

All seedlings were grown as described for Figure 2. At 12 h after the onset of illumination on day 11, plates were released in 10 μmol·m⁻²·s⁻¹ continuous red light (A) and (B). 5 μmol·m⁻²·s⁻¹ blue light (C) and (D), or constant darkness (E) and (F). LUC activity was recorded for 5 d. The asterisks indicate significant differences from Col (P < 0.001 as determined by Student’s heteroscedastic t test). Data are shown ± SE from 12 to 24 seedlings.

(A) Mean period length of LHY in Col and arr3,4,5,6 in red light.

(B) Representative average trace of LHY expression in Col (open squares) and arr3,4,5,6 (closed circles) in constant red light. Hatched bars, subjective night.

(C) Mean period length of LHY in Col and arr3,4,5,6 in blue light.

(D) Representative average trace of LHY expression in Col (open squares) and arr3,4,5,6 (closed circles) in constant blue light. Hatched bars, subjective night.

(E) Mean period length of LHY in Col and arr3,4,5,6 in the dark.

(F) Representative average trace of LHY expression in Col (open squares) and arr3,4,5,6 (closed circles) in the dark. Hatched bars, subjective night.
elocation in constant white light and light/dark cycles of white light. We observed long hypocotyls in the mutants under light/dark cycles but not in constant light (Figure 8D). However, we note that hypocotyl lengthening is not as pronounced as in the photoreceptor null mutants phyB-9 and cry1-304. Therefore, we conclude that ARR3 and ARR4 play a role in the control of hypocotyl length under light/dark cycles, possibly acting on phyB stability. However, their contribution in white light can only partially explain the long hypocotyl of phyB mutants.

Overexpression of ARRs Does Not Change Circadian Period

Overexpression of single genes is very often used to determine whether the activity of a gene is limiting. In the case of clock genes, overexpression of CCA1, LHY, TOC1, or ZTL leads to arrhythmicity (Schaffer et al., 1998; Wang and Tobin, 1998; Más et al., 2003a; Somers et al., 2004). Redundancy between CCA1 and LHY is evident, as either single mutant only shows a short period but the cca1 lhy double mutant becomes arrhythmic when released into constant light (Alabadi et al., 2002; Mizoguchi et al., 2002). We entrained seedlings overexpressing ARR4, ARR5, ARR6, or ARR9 (driven from the strong constitutive cauliflower mosaic virus 3SS promoter) to photocycles and measured cotyledon movement after transfer into constant light for 7 d. As shown in Figure 9, all overexpressing lines displayed a normal period length and circadian phase when assayed in white light. Although these results do not rule out a role for these ARRs in clock function, they do demonstrate that normal ARR activity is not limiting to clock function and that simple overexpression is insufficient to disrupt clock function. The amplitude of cotyledon movement was slightly affected during the first 3 d upon transfer into constant light, but this probably reflects the effect of ARR overexpression on cotyledon and petiole growth and not on the amplitude of the oscillator itself. Overexpression of phyB similarly causes a decreased amplitude in cotyledon movement, and petiole length in phyB-overexpressing plants is greatly shortened (data not shown) (Wester et al., 1994).

DISCUSSION

Light is one of the most potent environmental cues for the entrainment of circadian clocks. In Arabidopsis, phyB signaling is critical for the proper determination of circadian period (Somers et al., 1998) and phase (Salomé et al., 2002). Because the response regulator ARR4 interacts with phyB to positively modulate red light signaling (Sweere et al., 2001), we wished to determine whether ARR4 and other response regulators played a role in light signaling to the clock. Our results show that loss of ARR4 function is insufficient to impair clock function, probably because of the redundancy of ARR4 with ARR3. Indeed, the arr3,4 double mutant is altered in its circadian rhythms. Two distinct phenotypes were observed in arr3,4, of which one may be attributed to an effect on phyB activity. arr3,4 seedlings exhibit a long period in either red or blue light. By contrast, loss of PHYB lengthens the period of the clock under high fluence rates of red light but not blue light (Somers et al., 1998). In addition, the arr3,4 long period is seen even in the absence of light, when phyB is not active. Therefore, we do not think that the circadian phenotype of long period of the arr3,4 double mutant can be explained solely through interactions of ARR3 and ARR4 with phyB.

We hypothesize that the second circadian defect seen in arr3,4 seedlings is related to decreased phyB activity. Loss of phyB function results in a leading phase in white light (Salomé et al., 2002). If ARR3 and ARR4 positively modulate phyB signaling to the clock, one would predict that the arr3,4 mutant would have reduced phyB signaling, which would confer a leading phase. Indeed, when we recalculated the sidereal phases of arr3,4 and arr3,4,5,6 mutants in circadian time, which normalizes for the long period, we observed a leading phase relative to the wild type. Mutants with altered period length normally display a circadian phase defect: a long-period mutant will show a lagging phase, whereas a short-period mutant will exhibit a leading phase (Dunlap et al., 2004). Thus, the long period of arr3,4 would be predicted to also confer a lagging phase when determined in sidereal time. If the leading phase resulting from reduced phyB
Figure 8. The arr3,4 and arr3,4,5,6 Mutants Share phyB-Like Phenotypes.

The period and phase values for Col, arr3,4, and arr3,4,5,6 shown in Figure 2 are replotted in (A) and (B) as scatterplots of period against phase. Circadian time (CT) phase values were obtained by dividing sidereal phase values by the individual’s period length and then multiplying the value by 24 [CT = (phase/period) × 24].

(A) Sidereal phase and CT phase values for Col and arr3,4.

(B) Sidereal phase and CT phase values for Col and arr3,4,5,6.

(C) Box plot graph of sidereal phase and CT phase for Col, arr3,4, and arr3,4,5,6. The black box portion of the plot includes 50% of the data, with the white line representing the median. The error bars extend to the minimum and maximum data values. The asterisks indicate significant differences from Col (P < 0.001 as determined by Student’s heteroscedastic t test).

(D) Hypocotyl elongation of Col, arr3,4, and arr3,4,5,6 in constant white light (left) or photocycles (12 h of light and 12 h of dark; right). The single asterisks indicate significant differences from Col (P < 0.001 as determined by Student’s heteroscedastic t test). The double asterisks indicate significant differences from Col and arr3,4,5,6. Data shown are ± SD.
signaling and the lagging phase associated with the long period were quantitatively similar, although opposite in sign, the resulting phase would appear normal, consistent with the observed result. Thus, we conclude that simultaneous loss of ARR3 and ARR4 results in two separable defects. First, their loss attenuates phyB signaling to the clock. Independently, loss of ARR3 and ARR4 results in a long period, although the mechanism by which this occurs is not yet known (Figure 10).

Both type-A and type-B ARRs are involved in cytokinin signaling. Does the role of ARR3 and ARR4 in modulating clock function suggest that cytokinin signaling itself might regulate clock function? Several lines of evidence suggest that this is not the case. First, there is a gradual increase in cytokinin sensitivity with the progressive loss of more ARRs seen from arr3,4 through arr3,4,5,6 to arr3,4,5,6,8,9 mutants (Figures 1 to 4) (To et al., 2004). By contrast, the long period is similar in arr3,4 and arr3,4,5,6, whereas the period is wild type in arr3,4,5,6,8,9, arr5,6,8,9, and ahk3,4. Clearly, the period phenotype does not correlate with cytokinin sensitivity. Similarly, the phase alterations in response to increasing exogenous cytokinin treatments are qualitatively different from the long-period phenotype seen in the cytokinin-hypersensitive mutants arr3,4 and arr3,4,5,6. The long period of arr3,4,5,6 is not rescued by the introduction of a genomic copy of ARR5 (Figure 5H), although ARR5 rescues the cytokinin sensitivity of root elongation in arr3,4,5,6 (Figure 5H) (To et al., 2004). Moreover, the long period seen in these mutants is not exaggerated by cytokinin treatment, as period remains identical in treated and untreated seedlings, although circadian phase is delayed in the mutants to the same extent as seen in wild-type seedlings (Figure 5). Finally, we note that the hormone concentrations used here to produce an effect are quite high, which suggests that the lagging phase observed in the presence of exogenous hormone may not be physiologically relevant. Thus, we propose that the two type-A ARRs possess an as yet undescribed function that modulates the pace of the clock (Figure 10). This function is independent of cytokinin action, as exogenous applications of the hormone, albeit at high concentration, leads to a distinct clock response, that of lagging phase, in wild-type and mutant seedlings. Although ARR3 and ARR4 are expressed in most tissues of the plant, ARR3 mRNA levels are much lower than those of ARR4 (see Supplemental Figure 2 online). Nonetheless, ARR3 fully compensates for the loss of ARR4 for clock function; it is possible that ARR3 expression increases in the arr4 mutant, although this has not been tested.

Role of ARR3 and ARR4 in the Circadian Clock
Little is known of the mechanism of ARR function, especially with respect to roles in the clock. ARRs are evolutionarily related to the clock component TOC1, a member of the Pseudo Response Regulator family (Schaller et al., 2002). All five PRR genes play some role in the clock, because loss-of-function alleles in any affect the proper function of the circadian oscillator (Salomé and McClung, 2004). In contrast with type-B ARRs, which possess a DNA binding domain in their C terminus, type-A ARRs are not thought to directly regulate gene expression. Among type-A ARRs, only ARR3 and ARR4 show long, acidic, and Ser/Thr-Pro-rich C-terminal extensions. This C-terminal extension of ARR4 shows no obvious DNA binding motifs and is not able to replace the transactivation domain of GAL4 in yeast, suggesting that ARR4 lacks both DNA binding and transactivation functions (D’Agostino et al., 2000). Overexpression of ARR4 results in no circadian defects in white light, indicating that ARR4 activity is not limiting for proper clock function or, alternatively, that overexpression of both ARR3 and ARR4 may be required to change the pace of the clock. One possible explanation is that either protein alone is insufficient to mimic the activity of an ARR3–ARR4 complex. Similarly, the pseudorepressor regulators PRR7 and PRR9 are both important for clock function, and the prr7,9 double mutant exhibits a very long period, yet overexpression of PRR9 alone only results in slight period shortening (Matsushika et al., 2002; Farré et al., 2005; Salomé and McClung, 2005a).

If ARR3 and ARR4 do not regulate the clock at the level of transcription, they may regulate abundance and/or activity of the clock proteins. Period lengthening may be accomplished through a delay in the degradation or inactivation of a positive component of the clock, such as TOC1. Such period lengthening is seen in lines carrying the TOC1 minigene and in ztl mutants (Màs et al., 2003a, 2003b). The two response regulators may be negative regulators of TOC1 and might modulate the rate of translation, activation, or degradation of TOC1. ARR3 and ARR4 could compete with TOC1 for interaction with ZTL and therefore indirectly increase TOC1 protein levels and lengthen period length. An alternative explanation is that ARR3 and ARR4 are negative regulators of negative components of the clock, such as

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Figure 10. Tentative Model for ARR3 and ARR4 Function in and out of the Circadian Clock.

This model was adapted from Hwang and Sheen (2001). The cytokinin receptors AHK2, AHK3, and AHK4 perceive endogenous cytokinins and initiate a signal transduction cascade that leads to the phosphorylation and activation of type-B ARRs, which then induce the expression of primary cytokinin-responsive genes as well as of the type-A ARRs ARR3/4, ARR5/6, and ARR8/9. Type-A ARRs feed back to inhibit further type-B ARR activity. In addition, low, basal expression of ARR3 and ARR4 maintains the pace of the clock by acting on the expression, protein activity, and/or protein stability of a clock protein and modulates circadian phase by acting through phyB signaling into the clock. AHP, Arabidopsis histidine phosphotransmitter; RR, receiver domain of response regulator; BD, DNA binding domain; AD, transcription activation domain; P, phosphate.
the transcription factors CCA1 and LHY: in the absence of ARR3 and ARR4, increased abundance of activity of CCA1/LHY could lead to a longer period, as the repression of TOC1 expression would be maintained over a longer period of time, delaying the onset of the next cycle. Another attractive possibility calls upon the recently identified gene LUX ARRHYTHMO, a Myb-like transcription factor sharing high sequence similarity with the DNA binding domain of type-B ARRs (Hazen et al., 2005). LUX, like TOC1, is required for high expression of CCA1 and LHY. Thus, ARR3 and ARR4 might be positive regulators of LUX. Unfortunately, none of these possible models readily explains why the long period is suppressed when loss of ARR3 and ARR4 is combined with loss of ARR8 and ARR9.

That the simultaneous loss of ARR8 and ARR9 does not lead to a circadian defect, yet this double mutant combination suppresses the circadian phenotypes of arr3,4, is intriguing but difficult to explain. To et al. (2004) similarly observed complex interactions among ARR3, ARR4, ARR8, and ARR9. Consistent with our observations, loss of ARR8 and ARR9 suppressed the increased red light sensitivity seen in arr3,4. Similarly, overexpression of ARR4 and ARR8 had opposite effects on cytokinin sensitivity, suggesting that ARR4 is a positive regulator and ARR8 is a negative regulator of cytokinin signaling (Osakabe et al., 2002). At this time, however, we lack sufficient knowledge of the mechanisms by which any ARR functions in the clock to incorporate these functions into a detailed model. Perhaps they impinge on a common target, having opposite effects.

The long-period phenotype of arr3,4 seedlings is seen in all conditions tested (after light/dark and temperature cycles, in constant white, red, or blue light, and in the dark), indicating that ARR3 and ARR4 may target a protein that acts very close to, or even within, the clock itself. Two-hybrid screens have been performed with ARR4, but no known clock-related protein other than phyB was identified as a candidate interactor (Yamada et al., 1998). This leaves the exciting prospect of discovering a novel clock component on the basis of its interaction with ARR3 and ARR4.

METHODS

Plant Genotypes

All Arabidopsis thaliana genotypes (arr3, arr4, arr3,4, arr3,4,5,6, arr8,9, and arr3,4,8,9) were transformed with LUC constructs bearing translational fusions to the promoters of CCA1, LHY, and TOC1 (Salomé and McClung, 2005a), and primary transformants were selected as described (Salomé and McClung, 2005a). Resistant seedlings were allowed to self, and T2 or T3 seeds were analyzed.

Cotyledon Movement and LUC Assays

All rhythm assays were performed as described (Salomé et al., 2002; Salomé and McClung, 2005a). For cotyledon movement, seedlings were entrained for 5 d in photocycles (12 h of light followed by 12 h of dark). For LUC activity measurements, seedlings were entrained for 10 d in photocycles or thermocycles (12 h at 22°C followed by 12 h at 12°C). All rhythms were analyzed by fast-Fourier transform nonlinear least-square technique (Plautz et al., 1997).

For hormone treatments, all seedlings were entrained for 10 d in photocycles in the absence of hormone and were transferred to 96-well plates containing each hormone (kinetin, trans-zeaxtin, or benzyladenine) or 0.01% DMSO as a control carrier for untreated seedlings in the case of trans-zeaxtin and benzyladenine. Seedlings were further entrained in photocycles for an additional 1 d before being released into constant light. The addition of DMSO had no effect on clock period or phase. Kinetin was solubilized in slightly acidic water.

Generation of Constructs and Transgenic Plants

The ARR4 and ARR9 promoters were amplified by PCR from genomic DNA and cloned into pCR8/GW/TOPO (Invitrogen). The ARR4 promoter fusion includes 2824 bp of promoter sequence (from –2824 to the ATG), whereas the ARR9 promoter fusion contains 2081 bp of promoter sequence (from –2081 to the ATG). The promoter was then recombined into the LUC vector pZPBAR-DONR as described (Salomé and McClung, 2005a). The resulting binary vectors were introduced into Agrobacterium tumefaciens strain A5E1. Ecotype Columbia plants were transformed as described (Salomé and McClung, 2005a). Primary transformants were selected on MS plates supplemented with 2% sucrose and containing 12.5 μg/mL BASTA and 500 μg/mL carbenicillin.

For ARR-overexpressing lines, full-length cDNAs of ARR4, ARR5, ARR6, and ARR9 were amplified by PCR from a cDNA library made from wild-type Col light-grown seedlings, cloned into pENTR/D-TOPO vector (Invitrogen), and subcloned into the Gateway binary vector pGWB18 (Research Institute of Molecular Genetics) by LR recombination (Invitrogen). Each of the resulting constructs carried the constitutive cauliflower mosaic virus 35S promoter driving expression of an ARR cDNA with a 4X myc tag on the N terminus. The constructs were introduced into Col by Agrobacterium-mediated transformation. Transformants were selected on MS medium supplemented with 50 μg/mL kanamycin. Transgene expression was confirmed in homozygous kanamycin-resistant T3 seedlings by protein gel blotting of whole seedling protein extracts and detecting with anti-c-myc antibody (Roche Applied Science). One line per construct with high levels of protein expression was selected for cotyledon movement assays.

Accession Numbers

Arabidopsis Genome Initiative locus identifiers for the genes mentioned in this study are as follows: ARR3 (At1g59940), ARR4 (At1g10470), ARR5 (At3g48100), ARR6 (At5g62920), ARR8 (At2g1310), ARR9 (At3g57040), phyB (At2g18790), AHK3 (At1g27320), and AHK4 (At2g01830).

Supplemental Data

The following materials are available in the online version of this article.

Supplemental Figure 1. Exogenous Cytokinin Treatments Decrease the Amplitude of TOC1–LUC Expression Only at High Levels.

Supplemental Figure 2. Virtual RNA Gel Blot of ARR3 and ARR4.

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