Recurrent requirement for the m6A-ECT2/ECT3/ECT4 axis in the control of cell proliferation during plant organogenesis

Arribas-Hernández, Laura; Simonini, Sara; Hansen, Mathias Henning; Botterweg Paredes, Esther; Bressendorff, Simon; Dong, Yang; Østergaard, Lars; Brodersen, Peter

Published in:
Development

DOI:
10.1242/dev.189134

Publication date:
2020

Document version
Publisher's PDF, also known as Version of record

Document license:
CC BY

Citation for published version (APA):
RESEARCH ARTICLE

Recurrent requirement for the m⁶A-ECT2/ECT3/ECT4 axis in the control of cell proliferation during plant organogenesis

Laura Arribas-Hernández¹,², Sara Simonini²,* Mathias Henning Hansen¹,², Esther Botterweg Paredes¹, Simon Bressendorff¹, Yang Dong², Lars Østergaard² and Peter Brodersen¹,²,‖

ABSTRACT

mRNA methylation at the N6-position of adenosine (m⁶A) enables multiple layers of post-transcriptional gene control, often via RNA-binding proteins that use a YT521-B homology (YTH) domain for specific m⁶A recognition. In Arabidopsis, normal leaf morphogenesis and rate of leaf formation require m⁶A and the YTH-domain proteins ECT2, ECT3 and ECT4. In this study, we show that ect2 ect3 and ect2 ect3 ect4 mutants also exhibit slow root and stem growth, slow flower formation, defective directionality of root growth, and aberrant fruit and flower morphology. In all cases, the m⁶A-binding site of ECT proteins is required for in vivo function. We also demonstrate that both m⁶A methyltransferase mutants and ect2 ect3 ect4 exhibit aberrant floral phyllotaxis. Consistent with the delayed organogenesis phenotypes, we observe particularly high expression of ECT2, ECT3 and ECT4 in rapidly dividing cells of organ primordia. Accordingly, ect2 ect3 ect4 mutants exhibit decreased rates of cell division in leaf and vascular primordia. Thus, the m⁶A-ECT2/ECT3/ECT4 axis is employed as a recurrent module to stimulate plant organogenesis, at least in part by enabling rapid cellular proliferation.

KEY WORDS: m⁶A, YTH domain, ECT2, ECT3, ECT4, Plant organogenesis

INTRODUCTION

In post-embryonic development in plants, organogenesis is the result of activities of the stem cell niches in meristems at the shoot and root apices (Gailliochet and Lohmann, 2015; Pierre-Jerome et al., 2018). Organogenesis involves the distinct steps of initiation of organ primordia from meristematic cells, separation of primordia from meristems via boundary formation, and cellular proliferation and expansion coupled with differentiation (Bar and Ori, 2014; Du et al., 2018; Thomson and Wellmer, 2019; Wachsman et al., 2015). Key molecular principles governing these processes are signaling by the hormones auxin and cytokinin (Schaller et al., 2015), and establishment of mutually exclusive transcriptional programs via specific expression of antagonistic transcription factors (Drapek et al., 2017). In the main root meristem, the normally non-dividing quiescent center (QC) is defined by expression of the transcription factor WUSCHEL-LIKE HOMEobox (WOX5). An auxin maximum marks the WOX5-expressing QC cells that signal stem cell identity to immediately surrounding cells (Bilou et al., 2005; Forzani et al., 2014; Petersson et al., 2009; Sabatini et al., 1999; van den Berg et al., 1997), while cytokinin drives the transition to differentiation of the root stem cells (Dello Ioio et al., 2007) (see Drisch and Stahl, 2015 for a review). Conversely, at the shoot apical meristem (SAM), high cytokinin levels are present in the organizing center (OC), defined by expression of the founding WOX family member WUSCHEL (WUS). Stem cell identity in the adjacent central zone is specified by the non-cell autonomous action of WUS, and division of those stem cells is promoted by cytokinin (Chickarmane et al., 2012; Werner et al., 2003). Auxin, on the other hand, drives stem cell differentiation in the SAM, as lateral organ primordia with high cell division rates initiate from sites of auxin maxima at the periphery of the meristem (see Byrne, 2012 for a review). This process requires the repression of the KNOTTED-LIKE HOMEobox (KNOX) family of meristematic transcription factors that includes SHOOT-MERISTEMLESS (STM) (Hay and Tsiantis, 2010; Long et al., 1996). As the cells in that region engage in proliferation, the emerging primordium becomes an auxin sink, and depletion of auxin from the surrounding area prevents formation of adjacent primordia (Bartlett and Thompson, 2014; Benková et al., 2003; Heisler et al., 2005; Reinhardt et al., 2003). A number of microRNAs (miRNAs) has also been shown to reinforce robustness of the gene regulatory circuits specifying root, leaf and flower formation through regulation of the key transcription factors (Rubio-Somoza and Weigel, 2011). Nonetheless, the involvement of other mechanisms of post-transcriptional gene control in plant organogenesis remains poorly investigated.

Methylation of adenosine at the N6-position (m⁶A) in mRNA has recently emerged as a widespread mechanism of gene regulation (Zaccara et al., 2019). In eukaryotes, m⁶A is installed co-transcriptionally by a conserved, multi-subunit complex, the catalytic core of which consists of two methyltransferase-like proteins, METTL3 and METTL14 (Bokar et al., 1994, 1997; Liu et al., 2017). This heterodimer associates with additional proteins that are also required for m⁶A methyltransferase activity in vivo (Balaco and Soller, 2019). Their orthologs in plants include the splicing factor FKB12 INTERACTING PROTEIN of 37 kDa, FIP37 [WTAP/FI2(2) in metazoans] (Shen et al., 2016; Vespa et al., 2004; Zhong et al., 2008), the large protein of unknown biochemical function VIRILIZER (VIR) and the putative ubiquitin ligase HAKAI (Ružička et al., 2017). m⁶A is required for embryonic development beyond the
globular stage in plants (Růžička et al., 2017; Zhong et al., 2008) and is key to post-embryonic development, as hypomorphic vir-1 mutants or plants post-embryonically depleted of MTA exhibit stunted growth, severe developmental defects and a 75-90% reduction in m6A/A ratio compared with wild type (Bodi et al., 2012; Růžička et al., 2017). Similarly, post-embryonic depletion of FIP37 results in strongly delayed and defective leaf formation: the SAM overproliferates and fails to produce leaf primordia at its flanks, or does so with a strong delay compared with wild type (Shen et al., 2016). Many effects of m6A are mediated by RNA-binding proteins harboring a YT521-B homology (YTH) domain (Hartmann et al., 1999; Inami et al., 1998; Stoilov et al., 2002; Zhang et al., 2010) that is specialized for m6A recognition. The YTH domain contains a hydrophobic pocket consisting of highly conserved aromatic amino acid residues (the ‘aromatic cage’) that accommodate the N6-methyl group and thereby increase the affinity for m6A-containing RNA by 10- to 20-fold over unmethylated RNA of the same sequence (Li et al., 2014b; Luo and Tong, 2014; Theler et al., 2014; Xu et al., 2014; Zhu et al., 2014). The phylogeny of YTH domains defines two major classes, YTHDF and YTHDC, that may be found in several different proteins (Zuccara et al., 2019). YTHDF proteins are typically cytoplasmic and, in mammals, the molecular effects of the three family members (YTHDF1-3) can either be to accelerate the decay of m6A-containing mRNAs or to enhance their translation (Du et al., 2016; Kennedy et al., 2016; Li et al., 2017; Park et al., 2019; Sheng et al., 2020; Shi et al., 2017; Wang et al., 2014, 2015) (see Patil et al., 2018 for a review). The biological relevance of YTHDF2-mediated mRNA decay has been proposed in several germline and somatic cell differentiation-related processes (Ivanova et al., 2017; Li et al., 2018; Zhang et al., 2017; Zhao et al., 2017), while YTHDF1-mediated translational activation is required for some neuronal functions (Shi et al., 2018; Weng et al., 2018). Plant genomes encode an expanded set of YTHDF proteins, referred to as EVOLUTIONARILY CONSERVED C-TERMINUS (ECT), of which 11 are found in Arabidopsis (Li et al., 2014a; Scutenaire et al., 2018). The YTH domains of ECT1-11 contain all amino acid residues crucial for m6A-binding (Fray and Simpson, 2015) and m6A-binding activity has been directly shown for ECT2 (Wei et al., 2018). Furthermore, the m6A-binding capacity of ECT2 and ECT3 and its in vivo relevance are inferred from failure of m6A-pocket-disrupting mutants to restore the phenotypes of their corresponding knockout mutants (Arribas-Hernández et al., 2018; Scutenaire et al., 2018; Wei et al., 2018). In contrast, the downstream molecular effects of plant YTHDF proteins remain unclear (Arribas-Hernández and Brodersen, 2020). We recently found that the three YTHDF proteins, ECT2, ECT3 and ECT4, perform genetically redundant functions in leaf formation (Arribas-Hernández et al., 2018): ect2/ect3 double mutants complete post-embryonic leaf formation with a substantial delay compared with wild type, a phenotype that is exacerbated by additional mutation of ECT4. The leaves of ect2/ect3/ect4 triple mutants have serrated edges and a triangular (deltoid) shape that strongly resembles that of mta knockout plants (Arribas-Hernández and Brodersen, 2020; Shen et al., 2016). ect2/ect3 mutants also exhibit defective control of branching of unicellular epidermal hairs (trichomes), and weaker trichome branching defects can also be observed in ect3 (Arribas-Hernández et al., 2018) and ect2 (Arribas-Hernández et al., 2018; Scutenaire et al., 2018; Wei et al., 2018) single mutants. It remains unclear, however, whether the important functions of ECT2, ECT3 and ECT4 in leaf development rely on functions within the SAM or in developing leaf primordia, or both, and whether the involvement of the m6A-ECT2/ECT3/ECT4 module is specific to leaf formation or general to plant organogenesis. Similarly, the basis for the defects in embryogenesis and morphogenesis of roots, shoots and flowers of m6A-deficient mutants (Bodi et al., 2012; Růžička et al., 2017; Shen et al., 2016; Vespa et al., 2004; Zhong et al., 2008) remains ill defined. Most fundamentally, the issue of whether these important biological effects involve ECT proteins is still unresolved.

In this study, we show that the m6A-ECT2/ECT3/ECT4 module is necessary for correct root, flower and fruit formation. ECT2, ECT3 and ECT4 are highly expressed in rapidly dividing cells of organ primordia and only weakly expressed in peripheral meristematic cells, with little or no expression detectable in organizing or quiescent centers of inflorescence and root apical meristems. Consistent with these expression patterns, we observe slower growth of leaf primordia due to reduced rate of cell proliferation in ect2/ect3/ect4 triple mutants, but no clear delay in initiation of leaf primordia. Furthermore, the size of both vegetative and inflorescence meristems in ect2/ect3/ect4 triple mutants appears normal. Together, these observations establish that the m6A-ECT2/ECT3/ECT4 module is generally required for plant organogenesis, presumably via stimulation of cell proliferation in organ primordia.

RESULTS

Leaf primordia of ect2/ect3/ect4 mutants exhibit reduced cellular proliferation, but not delayed initiation

We first analyzed shoot apices of ect2-1/ect3-1/ect4-2 seedlings (referred to here as te234 for triple ect234, see Table 1 for abbreviations of all ect mutant allele combinations) to assess whether the SAM was visibly affected, and whether the initiation of leaf primordia was delayed. We observed no significant difference in SAM size between te234 and wild type from day 2 to 6 post-germination (Fig. 1A; see Fig. S1). Importantly, we could not detect any difference in the timing of emergence of leaf primordia, as it occurred between 2 and 3 days after germination (DAG) in both cases (Fig. 1A). On the contrary, counts of epidermal cells in leaf primordia as a function of time revealed that the estimated doubling time was significantly longer in te234 mutants than in wild type [Fig. 1B; t2(Col-0)=26.1 h, t2(te234)=34.5 h; P<0.001, see Materials and Methods], although no obvious difference in cell size was apparent at that stage. These analyses suggest that reduced growth rate of leaf primordia as a consequence of reduced cellular proliferation is the primary cause of the delayed leaf emergence in ect2/ect3/ect4 mutants. This is in contrast to fip37 knockout plants in which meristems overproliferate and form leaf primordia with a significant delay (Shen et al., 2016). Thus, m6A appears to affect leaf formation at least at two different levels: (1) initiation of leaf primordia via mechanisms that do not depend on ECT2, ECT3 and ECT4; and (2) growth of leaf primordia via mechanisms that involve rapid cellular proliferation and that require ECT2, ECT3 and ECT4.

Cellular proliferation of vascular stem cells is also reduced in ect2/ect3/ect4 mutants

To assess whether the low cell division rate also occurs in other developmental contexts, we examined vascular stem cells in
hypocotyls. Vascular stem cells, or procambium, continuously proliferate as they self-maintain and give rise to the mature vascular tissues, xylem and phloem. Procambial proliferation requires the transcription factor WUSCHEL-related HOMEOBOX4 (WOX4) (Hirakawa et al., 2010; Ji et al., 2010; Suer et al., 2011). We therefore analyzed cross-sections of wild-type and te234 hypocotyls, and included the wox4-1 knockout mutant (Hirakawa et al., 2010) as a control for procambial proliferation defects. Compared with wild type, te234 mutants showed a significant reduction in the number of vascular meristematic cells, but no significant differences in the number of mature xylem and phloem cells (Fig. 1C,D). This result suggests that ECT2, ECT3 and ECT4 also potentiate cell division in vascular stem cells, and hence points towards a general role of ECT2, ECT3 and ECT4 in promoting cell proliferation.

Arrest of growth in leaves of ect2/ect3/ect4 mutants is delayed

Our previous analyses of leaf formation suggested that te234 mutants may display two defects compared with wild type (Arribas-Hernández et al., 2018): (1) slower pace of leaf formation throughout rosette development; and (2) larger final leaf size despite later emergence. To rigorously document the latter phenomenon, we grew two independent allele combinations of ect2/ect3/ect4 under short-day conditions to prevent floral transition, and measured the area of juvenile leaves throughout the growth period (Fig. 2A-C). This quantification clearly demonstrated the two distinct defects suggested by our previous observations, and exposed the fact that leaf growth remains active for roughly two weeks longer in the mutants than in wild type, such that the final size of the first two pairs of leaves is 1.5- to 2-fold greater (P<0.0001 at 48 DAG for pairwise comparisons, with no significant differences between the two mutant alleles, see Materials and Methods) (Fig. 2B,C). Thus, both initial leaf growth rates and the timing of growth arrest are affected in ect2/ect3/ect4 mutants.

Leaf blades in the ect2/ect3/ect4 mutant exhibit deformities

We also noticed that irregular concavities in the leaf surface frequently occur in ect2/ect3/ect4 mutants (Fig. 2D). The formation of the flat leaf disc requires coordination of cell division rates and anisotropic growth along proximodistal and mediolateral axes (Fox et al., 2018). Defects in such coordination may cause mechanical stretch, and thereby give rise to surface irregularities.
Indeed, transverse histological sections through such concavities showed irregular numbers of cell layers and cell sizes, and disorganized disposition of cell types in ect2/ect3/ect4 compared with wild type (Fig. 2E). In particular, the intercellular spaces that occur exclusively on the abaxial side of the blade in wild-type plants were of more irregular sizes and occasionally appeared on the adaxial side of the mutant leaves, perhaps suggesting defects in leaf polarity (Fig. 2E). We conclude that leaf growth proceeds with multiple defects in rate, timing, coordination and patterning upon loss of the m6A-ECT2/ECT3/ECT4 axis.

ECT2, ECT3 and ECT4 are highly expressed at the root apex and throughout lateral root formation

We next studied the possible relevance of ECT2, ECT3 and ECT4 in root formation, as mutants deficient in m6A deposition display impaired root growth and gravitropism (Růžička et al., 2017), and m6A writer components are highly expressed in root meristems and/or lateral root primordia (Růžička et al., 2017; Zhong et al., 2008). Our analyses started with a thorough examination of ECT2, ECT3 and ECT4 expression patterns using stable lines of ECT2-mCherry, ECT3-Venus and ECT4-Venus fusions that showed strong expression in root tips (Fig. 3A), as previously reported (Arribas-Hernández et al., 2018).

Along the rest of the root, expression of all three proteins was highest at the sites of lateral root formation, with much weaker fluorescence seen in the vasculature, in particular for ECT2. More detailed analyses revealed high expression of ECT2, ECT3 and ECT4 in sites of lateral root initiation after the first periclinal division at stage II (Péret et al., 2009) (Fig. 3C). The signal remained high in all cells throughout the early stages of lateral root development (Fig. 3D), but was ultimately restricted to the proliferative area of newly formed lateral roots (Fig. 3E,F) in a pattern identical to that of the main root tips (Fig. 3A). To clearly visualize the exclusion of ECT2 expression from the QC, we introduced the auxin-responsive DR5:GFP reporter, with specific expression in cells of the QC and of the columella (Benkóvá et al., 2003; Ulmasov et al., 1997), into ECT2-mCherry lines. This analysis confirmed that ECT2 is not expressed in the QC itself, but in the adjacent cell division zone (Fig. 3G-I). It also revealed that although ECT2, ECT3 and ECT4 are highly expressed in cells experiencing an auxin maximum during early stages of lateral root formation, the expression of at least ECT2 is specifically excluded from the newly formed auxin maximum at emerging lateral root tips (Fig. 3G). Overall, we conclude that expression of ECT2, ECT3 and ECT4 in the root is particularly strong in proliferating cells undergoing differentiation.
The expression domain of MTA, but not of ECT2, ECT3 and ECT4, includes the QC

The exclusion of ECT2, ECT3 and ECT4 from the QC raises the issue of whether the ECT2, ECT3 and ECT4 expression pattern reflects the full range of cells in which m6A is used to control gene expression. To address this, we generated a C-terminal fusion of MTA to the turquoise fluorescent protein (TFP; MTA-FLAG-TFP) under the control of the MTA native promoter, and demonstrated its functionality by complementation of the embryonically lethal mta-2 knockout mutants (see Fig. S2). Confocal microscopy of lines expressing both MTA-FLAG-TFP and ECT2-mCherry demonstrated that, although MTA-FLAG-TFP and ECT2-mCherry are co-expressed in the division zone of the root meristem, only signal from MTA-FLAG-TFP is visible in the QC (Fig. 3J,K). Thus, although ECT2, ECT3 and ECT4 are key effectors of the m6A pathway in the division zone, other effectors, potentially other ECT proteins, are likely to mediate m6A functions in the QC.

Distinct subcellular localization of MTA and ECT2

We also used the MTA-FLAG-TFP/ECT2-mCherry co-expressing lines to compare the subcellular localization of the two proteins. Whereas MTA-FLAG-TFP was nucleoplasmic, ECT2-mCherry was predominantly cytoplasmic and did not overlap with MTA-FLAG-TFP (Fig. 3L). On the contrary, an area around the nucleus from which both proteins were excluded, presumably containing the nuclear envelope, was clearly visible in the merged images (Fig. 3L). These observations are consistent with a compartmentalized m6A-YTHDF pathway in which the m6A mark is written in the nucleus and read by ECT2 in the cytoplasm. Nonetheless, the resolution employed here does not allow us to totally exclude the presence of ECT2 in the inner nuclear periphery, as was previously suggested (Scutenaire et al., 2018; Wei et al., 2018).

ECT2, ECT3 and ECT4 are required for normal rate and directionality of primary root growth

We next analyzed whether ECT2, ECT3 and ECT4 are functionally relevant for root growth. Initial observations of root growth in single,
double and triple mutants suggested that ect2/ect3 double and, in particular, ect2/ect3/ect4 triple mutants exhibited slower root growth and more agravitropic behavior than wild type (Fig. 4A; see Fig. S3A,B), as do plants with reduced m6A levels (Růžička et al., 2017). In addition, ect2 single mutants exhibited exacerbated right slanting of root growth compared with the weak right slanting of Col-0 wild type (Grabov et al., 2005; Migliaccio and Piconese, 2001) (Fig. 4A). To quantify these phenotypes, we recorded the position of root tips every 24 h from 3 to 11 DAG to generate data for three informative morphometric characterizations: (1) a graphic description of root phenotypes as an overlay of the individual root growth trajectories; (2) root length and growth rate as a function of time; and (3) vertical and horizontal growth indices (VGI and HGI, respectively) (Grabov et al., 2005) (Fig. 4B-F; see Fig. S3C). To better describe slanting (Ferrari et al., 2000) and meandrous (agravitropic) growth, we also calculated partial HGI indices for...
every daily increment in growth, categorized them into left (−) and right (+) classes, and summed them to obtain cumulative left and right horizontal growth indices (HGIL and HGIR) (Fig. 4G). In this way, differences between genotypes could be quantified and the statistical significances of such differences assessed.

The quantitative analyses confirmed that roots of two independent ect2 single mutants display exacerbated right slanting (Fig. 4C), as revealed by a significantly higher positive HGI compared with Col-0 wild type (Fig. 4E). Accordingly, ect2 mutants had a higher [HGIR], but lower [HGIL] and VGI compared with wild type (Fig. 4E,F,G). Strikingly, we observed the opposite tendency in ect3 single mutants. Roots of two different ect3 mutants had negligible slanting as shown by near-zero HGI scores compared with the highly reproducible positive HGI (∼0.015-0.045) in Col-0 wild type (Fig. 4E). Correspondingly, ect3 mutants had a significantly lower [HGIR], but higher [HGIL] than wild type (Fig. 4G), thereby producing VGI scores similar to those of wild type (Fig. 4F).

In contrast, roots of two different allele combinations of ect2/ect3 double mutants exhibited meandrous growth rather than slanting (Fig. 4C): the VGI was low (comparable with that of ect2), which is indicative of non-vertical growth, but the HGI was near-zero (comparable to that of ect3) (Fig. 4E,F,G). Accordingly, [HGIL] and [HGIR] values were alike, but in this case both were higher than those of ect3 (Fig. 4G). Most importantly, ect2/ect3 seedlings had clearly reduced root growth rates (Fig. 4D; P<0.0001 for pairwise comparison between wild type and both ect2/ect3 double mutants at 7-11 DAG). Finally, the single mutation of ect4 did not produce significant differences in root growth rate or directionality, and ect2/ect4 resembled ect2, whereas ect3/ect4 resembled ect3 (see Fig. S4). However, the slow root growth of de23 seedlings was exacerbated by mutation of ect4 (P<0.0001 for pairwise comparison between de23 and te234 during 6-11 DAG) (Fig. 4C,D). We conclude that, similar to their role in leaf formation (Arribas-Hernández et al., 2018), ECT2 can promote the rate of root growth, consistent with their high expression in the division zone of root meristems. However, specific, and even opposite, effects of ECT2 and ECT3 can be detected in root growth directionality, pointing to the existence of either specific mRNA targets of ECT2 and ECT3, or to differences in their mode of mRNA regulation.

Binding to m^6^A is required for the function of ECT2 and ECT3 in root morphogenesis

To test whether the m^6^A-binding activity of ECT2 is involved in root slanting, we characterized root growth of ect2-1 mutants expressing either ECT2-mCherry or its aromatic cage mutant, ECT2^W246A-mCherry, under the control of the ECT2 native promoter (Arribas-Hernández et al., 2018). Interestingly, expression of the wild-type transgene, but not the m^6^A-binding deficient mutant, not only rescued the enhanced right slanting of ect2-1, but also inverted the root growth directionality to a left slanting, contrary to the natural tendency of the Col-0 ecotype (Grabov et al., 2005; Migliaccio and Piconese, 2001), as seen by negative HGI values and [HGIL]≥[HGIR] (Fig. 5A-E). As ECT2-mCherry levels in the transgenic lines exceed endogenous ECT2 levels (Fig. 5F), we conclude that root growth directionality exhibits exquisite ECT2 dose dependence: exacerbated right slanting is seen in ect2 mutants, while even weak ECT2 overexpression causes left slanting.

Next, we tested whether the m^6^A-binding activities of both ECT2 and ECT3 are necessary for the correct growth rate of roots, using transgenic lines expressing either ECT2-mCherry, FLAG-ECT3 or their corresponding aromatic cage mutants, ECT2^W246A-mCherry and FLAG-ECT3^W246A, but this time in the te234 mutant background (Arribas-Hernández et al., 2018). These experiments showed that expression of the wild-type ECT2 and ECT3 transgenes largely rescued the growth defects observed in roots of te234 mutants, while the m^6^A-binding-deficient versions failed to do so (Fig. 5A,B). Also in this case, lines slightly overexpressing ECT2-mCherry showed left slanting (Fig. 5A,C,E-F), while te234 plants partially complemented by FLAG-ECT3 recapitulated the magnitude of right slanting seen in de24 mutants (compare Fig. 5 with Fig. S4). Thus, primary root growth, including both rate and directionality, requires the m^6^A-ECT2/ECT3/ECT4 module.

ECT2, ECT3 and ECT4 are highly expressed in floral primordia

We next examined reproductive tissues. Expression of fluorescent fusions of ECT2, ECT3 and ECT4 was detected throughout the inflorescence meristematic area, but the signal was higher in cells of young floral primordia than in the inflorescence meristem (IM) (Fig. 6A). This difference was not due to attenuation of the signal with tissue depth, because orthogonal views of z-stacks of meristems revealed that floral primordia had higher ECT2-mCherry fluorescence intensities than the IM at comparable depths (Fig. 6B,C; Fig. S5A,B). Furthermore, when we examined transgenic lines co-expressing MTA-FLAG-TFP and ECT2-mCherry, we observed nuclear TFP signal throughout the meristem, including in the central zone devoid of ECT2-mCherry signal (Fig. 6D), reminiscent of the pattern observed in root tips. Again, the subcellular localizations of MTA-FLAG-TFP and ECT2-mCherry were complementary, with MTA-FLAG-TFP being nucleoplasmic and ECT2-mCherry being mainly cytoplasmic (Fig. 6E), as observed in roots.

To validate the expression pattern displayed by the fluorescent fusion proteins and to characterize the expression of ECT2 and ECT3 in floral organ primordia, we performed RNA in situ hybridization with probes specific for ECT2 and ECT3 mRNAs (Fig. 6F; see Figs S5C, S6 and S7). Expression of ECT2/3 mRNA was highest in young floral primordia (stages 1-2; Smyth et al., 1990), while weaker signal was observed in the IM (Fig. 6F). This result is in agreement with the fluorescence microscopy, and therefore strongly supports accurate reflection of the endogenous expression pattern by our fluorescent reporters. At later stages, the signal was located at sepal, petal and stamen primordia (Fig. 6F-H), but only at the edges of developing sepal and petals, and in gametes of more mature flower buds (Fig. 6G-J; see Figs S6H and S7G). In summary, ECT2 and ECT3 are mainly expressed in young floral and floral organ primordia undergoing cell proliferation and differentiation. The IM itself shows less expression, mostly in the peripheral zones and little expression is seen in more developed organs. Thus, also in flower formation, ECT2 and ECT3 (and possibly ECT4) exert their functions mainly in rapidly dividing cells.

ect2/ect3/ect4 and m^6^A writer mutants exhibit defective floral phyllotaxis

The strong expression of ECT2 and ECT3 in early-stage floral primordia led us to examine possible roles of ECT2 and ECT3 in phyllotaxis, i.e. the arrangement of lateral organs on the stem, as that is determined by the sites of primordium initiation. In Arabidopsis, the two cotyledons and the first pair of true leaves exhibit an opposite decussate pattern: 180° from one another, and in a 90° twist from the preceding pair. From the third leaf onwards, new organs emerge one at a time forming a spiral with a divergence angle of ~137.5° (the golden angle; Lüttege and Souza, 2019), albeit with some stochastic variability (Mirabet et al., 2012). To characterize
phyllotaxis quantitatively, we measured divergence angles between successive flowers of wild type and two different allele combinations of ect2/ect3/ect4. The full circle was divided into 16 intervals of 22.5° (i1-i16), such that 0° falls in i1, the golden angle in i7 and 180° in i9 (Fig. 7A) (Prasad et al., 2011). We assigned each measurement to an interval and calculated their frequencies (f), resulting in the distributions shown in Fig. 7B. Although the wild-type distribution peaks sharply in i7 as expected, te234 and Gte234 distributions have an additional prominent peak in i9, indicative of organs diverging by 180° from one another almost as frequently as by 137.5° (fi7/fi9 ∼11 in wild type versus fi7/fi9 ∼1.5 in ect2/ect3/ect4; P<0.0001 for both allele combinations, see Materials and Methods). These observations establish that ect2/ect3/ect4 triple mutants exhibit defective floral phyllotaxis, and therefore imply defects in meristem function, perhaps related to auxin distribution or responsiveness.

Phyllotaxis has not previously been examined in m6A writer mutants. Therefore, to assess whether the phyllotaxis defect of ect2/ect3/ect4 mutants may be connected to m6A, we measured divergence angles in hakai-1 knockout mutants, with m6A/A ratios 35% lower than those of wild type (Ružička et al., 2017), and in a more severely m6A-deficient transgenic line with low post-embryonic MTA expression in the mta-1 knockout background (ABI3pro:MTA/mta-1) (Bodi et al., 2012). Clear phyllotaxis defects were observed in...
both cases (Fig. 7C). The defects were more pronounced in AB3pro:MTA/mta-1, with a decrease in f7/f9 almost identical to what we found in ect2/ect3/ect4 plants, while hakai-1 mutants had intermediate values [f7/f9 ∼ 8 in wild type versus f7/f9 ∼ 3 in hakai-1 (P < 0.001), and f7/f9 ∼ 1.3 in AB3pro:MTA/mta-1 (P < 0.0001), see Materials and Methods]. We also observed additional defects typical of m6A deficiency in main stems of hakai-1, albeit with low penetrance (see Fig. S8 in the supplementary material). Finally, although we attempted to measure phyllotaxis in MT4 knockdown plants expressing an artificial microRNA directed against MTA (amiR-MTA; Shen et al., 2016), the low number of individuals producing stems and their extremely short to non-existing internodes...
made the quantification impossible. Nevertheless, a clear defect could be visually determined (Fig. 7D). We conclude from these observations that m6A is required for normal phyllotaxis, and that ECT2, ECT3 and ECT4 are major effectors of this function.

Control of flowering time and stem growth are defective in ect2/ect3/ect4 mutants

We next examined whether ECT2, ECT3 and ECT4 might influence the transition from vegetative to reproductive meristem (flowering time) and stem growth, as casual observation of ect2/ect3/ect4 mutants revealed late bolting and shorter than those of wild-type plants at any given time (Fig. 7E; Fig. S9). However, measuring such traits in plants with slow growth altogether is not trivial, as late flowering and shorter stems might be explained by the previous delay in rosette development. To circumvent that problem, we focused on two well-defined points in development: at the time of flowering, we counted number of leaves (NL) and number of days after germination (DAG), and at the time of opening of the 10th flower, we measured the main stem length (SL) and counted the number of days after bolting (DAB) (see Materials and Methods for additional details). The combination of these measurements also allowed us to calculate the rate of leaf production until the floral transition (number of leaves per day, NLD=NL/DAG), and the stem growth per day (SGD=SL/DAB) during the maturation of the first 10 flowers. We measured these parameters in a complete collection of single, double and triple ect2, ect3 and ect4 mutants, along with transgenic lines expressing wild-type or cage-mutant transgenes of ECT2 and ECT3 in a te234 background. The results show that ect2/ect3 and ect2/ect3/ect4 mutants exhibit defective timing and growth rate during the reproductive phase of development (Fig. 7F). These effects manifest themselves as: (1) early flowering in terms of plant maturity, i.e. with fewer rosette leaves; (2) delayed flowering measured in time, likely as a result of a lower rate of leaf production; (3) reduced stem growth; and (4) slower maturation of flowers, although this latter phenotype only reached formal statistical significance in te234 mutants. Some single and double mutant combinations other than ect2/ect3 also showed differences from wild type in varying subsets of these parameters, and, importantly, always with the same tendency as that seen in ect2/ect3 or ect2/ect3/ect4 mutants, albeit generally with less significance and/or less pronounced difference (see Figs S10 and S11). Of note, complementation by the wild-type ECT2/ECT3 genes, but not their m6A-binding deficient variants, was clearly observed for the parameters DAG, NLD, SL and SGD (see Figs S10 and S11).
establishing that functions of ECT2/ECT3 in control of flowering time and stem growth also require m6A-binding activity. Finally, we also sporadically observed defects in the initial direction of the growth of the stem in te234 mutants (Fig. 7G), resembling the gravitropic defects seen in roots (Fig. 4). In summary, the slow growth of the main inflorescence expands our earlier observations of delayed growth to include not only leaves (Arribas-Hernández et al., 2018) and roots (Fig. 4D), but all vegetative aerial parts and reproductive tissues. Hence, the m6A-ECT2/ECT3/ECT4 module is generally required for organogenesis.

m6A-binding capacity of ECT2, ECT3 and ECT4 is required for correct floral patterning

As our RNA in situ hybridizations revealed high ECT2/ECT3 mRNA abundance in all floral organ primordia (sepals, petals, stamens and ovules) at early stages, we investigated whether ECT2, ECT3 and ECT4 are necessary for correct floral patterning. Indeed, preliminary inspections revealed defects in the number, morphology and disposition of petals and stamens in ect2/ect3 and ect2/ect3/ect4 mutants (Fig. 8A). In particular, petals were often misplaced from the characteristic cross-disposition in Brassicaceae (Cruciferae), and showed aberrant morphology or inverted orientation (pointing inwards) (Fig. 8A). We chose petals to quantify floral defects, as their size and accessibility allow for a quick assessment of their number. We counted the number of petals in the first 10 or fewer flowers of main inflorescences of combinations of single, double and triple ect2, ect3 and ect4 mutants. For ect2/ect3/ect4, we could not always include 10 flowers because some plants produced fewer flowers than that. First, we combined data from different alleles of the same genes after verifying the absence of significant differences in petal numbers between them (P=0.76, see Materials and Methods). We then tested differences in petal numbers between wild type and each combination of ect2, ect3 and ect4 mutants. The analysis revealed a significant difference in the number of petals of ect2/ect3 and ect2/ect3/ect4 plants compared with wild type, with five- and six-petaled flowers being more frequent in the mutants (Fig. 8B). Additional mutation of ECT4 significantly exacerbated the defects of the two ect2/ect3 double mutants (Fig. 8B). Importantly, correct floral patterning requires the m6A-binding activity of ECT2, ECT3 and ECT4, because expression of wild type and the cage-mutant transgenes in te234 yielded highly significant differences (Fig. 8C), whereas no differences were detected in comparisons between the complemented lines and their double mutant equivalents (de34 for te234/ECT2-mCherry, de24 for te234/FLAG-ECT3 and de23 for te234/ECT4-Venus, P>0.05 in all cases; Fig. 8B,C). Interestingly, we observed a tendency of cage-mutant transgenes to exacerbate the te234 petal phenotype (Fig. 8B,C), significant for te234/FLAG-ECT3W283A lines (P=0.014). Such dominant-negative effects may arise by competition for binding to other effectors of the m6A pathway through interactions via their intrinsically disordered regions (IDRs).

ECT2 and ECT3 play a role in the determination of fruit shape and size that is dependent on their m6A-binding capacity

We finished our analysis by examining fruits of ect2/ect3 and ect2/ect3/ect4 mutants. The siliques of de23 and te234 mutants were wider than in wild type and, particularly in the triple mutant, they sometimes contained three carpels that could be either completely separated or partially fused (Fig. 9A,B). This increase in fruit width...
was statistically significant (Fig. 9C) and was mainly due to a lateral expansion in the surface of the carpels (Fig. 9B), reminiscent of the wider laminas observed in juvenile leaves (Fig. 2B). No consistent abnormalities in fruit width could be observed for other ect mutants [e.g. the effect seen in ect-2 was not corroborated by the other ect3 allele (ect3-1)]. As with all other phenotypes tested, aberrant siliques were rescued by expression of wild type, but not m6A-binding deficient ECT2/ECT3 transgenes (Fig. 9D,E).

Although we did not find significant differences in fruit length that were consistent among different combinations of ect2, ect3 and ect4 mutants compared with wild type, we observed a higher frequency of aberrant fruits exhibiting lengths smaller than 10 mm (see Fig. S12 in the supplementary material), and/or distorted shapes (Fig. 9F) in ect2/ect3 and ect2/ect3/ect4 mutants. Furthermore, close inspection of the distal part of te234 fruits by scanning electron microscopy (Fig. 9G) revealed that the valve tips often extended their apical growth, a characteristic that is pronounced in close relatives of Arabidopsis with heart-shaped siliques, such as members of the Capsella genus. Such overgrowth has been associated with sequence variation in the regulatory domains of the fruit-tissue identity gene INDEHISCENT (IND) in Capsella species (Dong et al., 2019). Indeed, our analysis shows that the apical overgrowth of siliques from te234 mutants is reminiscent, albeit milder, of siliques from Arabidopsis ind-2 mutants expressing Capsella rubella IND (Dong et al., 2019) (Fig. 9G).

Finally, we examined the disposition of seeds inside the siliques of de23 and te234 mutants by simple inspection of cleared tissue. This analysis revealed that, in both mutants, seeds are placed within the siliques in a more irregular pattern than in wild type (Fig. 9H). In particular, both mutants showed increased occurrence of missing seeds (Fig. 9H), indicative of either defective ovules, failed fertilization or aborted seeds.

**DISCUSSION**

A recurrent role of m6A-ECT2/ECT3/ECT4 in plant organogenesis: an accelerator of primed stem cell proliferation?

The main conclusion of the present work is that the m6A-ECT2/ECT3/ECT4 module has a ubiquitous role in plant organogenesis: ect2/ect3 and/or ect2/ect3/ect4 mutants exhibit specific defects in the architecture of leaves, stems, flowers, fruits and roots, which are formed with a delay. Importantly, these defects can be rescued by wild type, but not by m6A-binding deficient mutants, providing a strong argument that defective reading of at least part of the m6A program by ECT2, ECT3 and ECT4 causes aberrant development. Organogenesis involves both establishment of a population of primed stem cells deriving from pluripotent meristems, and coordinated cell division, differentiation and expansion in these newly established organ primordia. It is, therefore, of crucial importance for the...
understanding of the biological relevance of the m6A-ECT2/ECT3/ECT4 program to define which of these processes are under its control. Here, we propose that promoting cell division in organ primordia is the key function of this subclade of m6A readers for three reasons. First, it is consistent with our expression analyses of ECT2, ECT3 and ECT4 that show highest expression in the rapidly dividing cells of all organ primordia and division zones examined. Second, leaf primordia form roughly at the same time in wild type and ect2/ect3/ect4 mutants, but the cell division rate in young leaf primordia is reduced compared with wild type. Third, vascular stem cells are less numerous in hypocotyls of ect2/ect3/ect4 seedlings than in wild type, further proving proliferation defects. We note that stimulation of cellular proliferation by m6A-YTHDF2 has also been observed in early zebrafish embryos (Zhao et al., 2017) and in mammalian cell culture (Fei et al., 2020). Nonetheless, biologically relevant m6A-YTHDF function in animals often involve developmental transitions in differentiation trajectories, and is thought to rely on YTHDF-mediated stimulation of decay of methylated mRNAs encoding key regulatory factors (Ivanova et al., 2017; Li et al., 2018; Zhang et al., 2017; Zhao et al., 2017). Whether the stimulated cell proliferation by m6A-YTHDF axes in early vertebrate embryos and in plant organ primordia also reflects similarities at the level of molecular function must await identification of mRNA targets of proven biological relevance in both systems.

m6A-ECT2/ECT3/ECT4: only one of several m6A-dependent regulatory axes in development

Mutants with reduced m6A levels (Bodi et al., 2012; Ružička et al., 2017; Shen et al., 2016) show striking phenotypic similarities with ect2/ect3/ect4 mutants. These include delayed emergence of juvenile leaves with deltoid shape and serrated edges (see Arribas-Hernández and Brodersen, 2020 for a direct comparison), slow root and stem growth, root agranulotropism, aberrant flower morphogenesis, increased trichome branching and, as shown here, defective phyllotaxis. Additionally, delayed floral transition has been described in mutants of the m6A-demethylase ALKBH10B (Duan et al., 2017) and, although the vascular defects described by Ružička et al. (2017) have not been studied in ect2/ect3/ect4 mutants yet, the defects in vascular stem cell proliferation (Fig. 1C,D) may be indicative of another similarity. These observations highlight the importance ECT2, ECT3 and ECT4 as effectors of the m6A pathway in plants. Nevertheless, mta, mth, lip37 and vir knockout embryos arrest at the globular stage (Ružička et al., 2017; Vespa et al., 2004; Zhong et al., 2008), and severe post-embryonic m6A depletion causes overproliferation of the SAM and strongly delayed initiation of leaf primordia (Shen et al., 2016), phenotypes not observed in ect2/ect3/ect4 mutants. The most obvious explanation for these differences is the involvement of the remaining YTH-domain-encoding genes. In that regard, it is interesting that cells in the root QC and the organizing center in the IM express MTA1 but not ECT2, ECT3 and ECT4, and mRNA-Seq data from sorted root QC cell populations reveals expression of ECT genes other than ECT2, ECT3 and ECT4 (Brady et al., 2007). Thus, methylated mRNAs in these cells may be regulated by alternative m6A readers. This could account, for example, for the above-mentioned differences in SAM size and initiation of leaf primordia. Furthermore, the only phenotypes described for plants with mild m6A deficiency that disagree with those of ect2/ect3/ect4 mutants are bushy rosettes with small and supernumerary leaves, and severe loss of apical dominance as described by Fray and colleagues (Bodi et al., 2012; Ružička et al., 2017), perhaps related to the multiple SAMs reported by Yu’s group (Shen et al., 2016). Interestingly, we have seen such phenotypes among a few primary transformants expressing ECT2/ECT3 transgenes, raising the possibility that the function of other ECTs may be knocked down in these plants, either by competition due to transgene misexpression in the OC, or perhaps due to co-suppression (Napoli et al., 1990) via siRNAs targeting the highly similar mRNA regions encoding YTH domains. In summary, we propose that ECT2, ECT3 and ECT4 are the main mediators of m6A-stimulated proliferation of primed stem cells in organ primordia, but that distinct m6A-ECT axes control behavior of organizing centers and pluripotent stem cells in meristems.

Redundant and specific functions of ECT2 and ECT3

The phenotypic analyses in this and our previous work (Arribas-Hernández et al., 2018) show that defects in leaf, root and stem growth, floral patterning, and silique morphology arise only upon simultaneous knockout of ECT2 and ECT3. Taken together with their overlapping expression patterns, we consider this to be evidence that ECT2 and ECT3 act redundantly to stimulate growth and proliferation in organ primordia. Although hints that ECT2 and ECT3 may not always be fully redundant have also come from the observation that both single knockouts cause mild trichome branching defects (Arribas-Hernández et al., 2018), this cannot be considered proof of non-redundant molecular function, as lower dosage may cause weak phenotypes in either single mutant and a stronger phenotype in the double mutant, as observed (Arribas-Hernández et al., 2018). Here, we provide a clear example in which ECT2 and ECT3 have different, even opposite, rather than redundant, functions: ECT2 promotes leftwards root slanting while the opposite is true of ECT3. Given the exquisite dose dependence on ECT2 of root slanting, root directionality in Arabidopsis may be an ideal system for deciphering the in vivo relevance of competition between YTHDF proteins, a fundamental issue that also remains controversial in animals (Zaccara et al., 2020). We note in this regard that the different functions of ECT2 and ECT3 may relate to microtubule assembly, as mutations in tubulin subunits as well as microtubule-associated proteins (MAPs) produce either right or left slanting, depending on how the mutation affects the arrangement of protofilaments in cortical microtubules (Furutani et al., 2000; Ishida et al., 2007; Marinelli et al., 1997; Rutherford and Masson, 1996; Thitamadee et al., 2002) (see Smyth, 2016 for a review). Interestingly, mRNAs encoding 14 out of the 15 Arabidopsis α and β-tubulin subunits, as well as MAPs known to affect slanting such as SPIRAL1 (Furutani et al., 2000; Nakajima et al., 2004; Sedbrook et al., 2004), carry m6A (Parker et al., 2020). Future studies comparing ECT2 and ECT3 target sets might clarify the origin of the distinct root phenotypes of the single mutants.

We also note that the existence of specialized functions of ECT2 and ECT3 is consistent with their sequence and pattern of evolutionary conservation. Although ECT2 and ECT3 belong to the same subclade of YTHDF proteins (Scutenaire et al., 2018), their IDR s that might exert the effector functions (Du et al., 2016; Park et al., 2019; Ries et al., 2019; Wang et al., 2014; Zhang et al., 2019) have different lengths and compositions. Importantly, most dicot genomes encode orthologs of both ECT2 and ECT3 (Scutenaire et al., 2018), supporting the model of at least some distinct functions of biological importance.

Compensation of reduced proliferation rates may contribute to ect2/ect3/ect4 phenotypes

It is a puzzling observation that leaves of ect2/ect3/ect4 mutants grow larger than wild type despite a reduced rate of cell division at early stages. Cells recruited into leaf primordia first proliferate in coordination with cytoplasmic growth, keeping their size constant,
and subsequently enlarge their volumes through cycles of endoreduplication. Although the final size of the leaf is crucially influenced by the duration and efficiency of the proliferation phase (Czesnick and Lenhard, 2015), lateral organs can reach normal dimensions despite impaired cell division thanks to a mechanism called compensation (Foard and Haber, 1961), in which abnormally enhanced cell expansion is triggered by defective cell proliferation in leaf primordia (Tsukaya, 2002). Accordingly, compensation is seen in, for example, mutants with lesions in genes encoding core cell cycle regulators, positive regulators of cell proliferation and ribosomal proteins (Horiguchi and Tsukaya, 2011). Interestingly, mRNAs encoded by many of these genes present m6A marks in Arabidopsis seedlings (Parker et al., 2020), e.g. AE7, ER, FUGU5/AVP1, PFL2, RPS21B or RPS28B. Thus, it is possible that mis-regulation of these factors causes reduced cell proliferation and compensation in ect2/ect3/ect4 mutants. Indeed, such an effect would be in line with our observations of occasional larger cells in the concavities of te234 mutant leaves. Compensation might also explain the expanded surface of the fruit valves and the increased trichome branching of ect2/ect3 and m6A-writer mutants (Arribas-Hernández et al., 2018, Bodi et al., 2012; Scutenaire et al., 2018; Vespa et al., 2004; Wei et al., 2018) if the compensatory cell enlargement is due to overstimulated endoreduplication (Horiguchi and Tsukaya, 2011). Nevertheless, mutants exhibiting compensation typically produce leaves that barely reach wild-type size and do not grow bigger, as in the case of ect2/ect3/ect4. An explanation for their larger final size could involve mis-regulation of additional targets that would cause a more extreme cell expansion and/or extension of the proliferation phase. Interestingly, knockdown of MTA also results in delayed leaves that resemble those of ect2/ect3/ect4 mutants, although in this case their size remains small (Arribas-Hernández and Brodersen, 2020). It is possible, however, that a more profound defect in cell proliferation in these mutants may not be fully counteracted by compensation.

m6A-ECT2/ECT3/ECT4 and auxin

As a final note, we wish to point out that the phenotypes of plants defective in the m6A pathway described here and previously (Arribas-Hernández et al., 2018; Bodi et al., 2012; Řížičkova et al., 2017) are very similar to those with impaired auxin function, e.g. defects in gravitropism (Su et al., 2017), phyllotaxis (Bhatia and Heisler, 2018), leaf shape and size (Sluis and Hake, 2015), and floral development (Thomson and Wellmer, 2019). These similarities raise the interesting question of how much of these phenotypes are explained by mis-regulation of key components of the auxin signaling pathway, including auxin biosynthesis factors, transporters and auxin response factors. In this way, our study provides solid guidelines for future molecular and genetic investigations based on identification of direct mRNA targets of the m6A-ECT2/ECT3/ECT4 axis.

MATERIALS AND METHODS

Oligonucleotide sequences

Sequences of all oligonucleotides used in this study are available in Table S1.

Growth conditions

Growth conditions are detailed in Arribas-Hernández et al. (2018). Briefly, we sterilized seeds using a 2 min incubation in 70% ethanol followed by 10 min in 1.5% NaOCl and 0.05% Tween-20, two H2O washes, and 2-5 days of stratification at 4°C in darkness. Seedlings were germinated and grown on Murashige and Skoog (MS)-agar medium (4.4 g/LSalt mixture, 10 g/L sucrose and 8 g/L agar; pH 5.7) at 21°C, receiving light intensities of ∼70 μmol m2 s−1, and 16 h light/8 h dark supplemental light cycle as default. To characterize root growth, we used 9.5×9.5 cm square MS (1% agar) plates, placed vertically on racks. Short-day conditions were also used as specified in the text, with 8 h light/16 h dark supplemental light cycle. To assess phenotypes of adult plants, 8-day-old seedlings were transferred to soil and maintained in Percival incubators at 21°C/day/17°C-night temperature at a light intensity of ∼100 μmol m−2 s−1, and the light regime of choice in each case. We used Philips fluorescent tubes TL-D 90 De Luxe 36 W as the light source.

Plant material

All lines used in this study are in the Arabidopsis thaliana Col-0 ecotype. The mutant alleles or their combinations were as follows: ect2-1 (SALK_002255) (Arribas-Hernández et al., 2018; Scutenaire et al., 2018; Wei et al., 2018), ect2-3 (GK_132F02), ect3-1 (SALKseq_63401), ect3-2 (GABLseq_487H12.1), ect4-1 (GK_241H02), ect2-1/ect3-1 (dec2), ect2-3/ect3-2 (Gde23), ect2-1/ect3-1/ect4-2 (te234) (Arribas-Hernández et al., 2018), wox1-1 (GK_462G01) (Hirakawa et al., 2010), mta-2 (emb1706-2, Line 41510) (McElver et al., 2001), hakii-1 (GK_217A12) (Růžičkova et al., 2017) and ind-2 (Liljegren et al., 2004), ect2-3/ect3-2/ect4-2 (Glo234) was generated by genetic cross between Gde23 and ect4-2 using the same method described by Arribas-Hernández et al. (2018).

The transgenic lines ABI3pro:MTA-mt1a-1 (Bodi et al., 2012), amiR-MTA (Shen et al., 2016) and At_ind-2 Cr_INDpro:IND-GFP (Dong et al., 2019) have been previously described. All transgenic lines expressing ECT2pro:ECT2-mCherry/ECT2ter, ECT2pro:ECT2W444-mCherry/ECT2ter, ECT3pro:FLAG-ECT3-ECT3ter, ECT3pro:FLAG-ECT3W283A-ECT3ter, ECT3pro:Venus-ECT3ter and ECT4pro:ECT4-Venus/ECT4ter are also described (Arribas-Hernández et al., 2018) or generated by floral dip in additional, single, double or triple mutants of ect2, ect3 and ect4, using the same plasmids and methods (Arribas-Hernández et al., 2018). Lines expressing ECT4pro: ECT4W444-Venus/ECT4ter were produced in the same way with a plasmid derived from pCAMBIA3300-ECT4pro:ECT4-Venus/ECT4ter by site-directed mutagenesis, as also described by Arribas-Hernández et al. (2018), with primers LA769-LA770. The mutation was detected by PCR with primers LA771-LA772 followed by restriction digestion with SatI. In general, line selection was first carried out in ect2/ect3 and ect2/ect3/ect4 knockout backgrounds and ∼30 T1s were pre-selected based on phenotypic complementation by visual inspection. Subsequently, lines with single insertions, no signs of silencing and comparable levels of the transgenic protein in the T2 generation entered the final selection (Arribas-Hernández et al., 2018). For the transgenic lines in single mutant backgrounds used in this work, we chose lines with expression levels similar to those able to complement the double or triple mutant phenotypes, as complementation of the ect2, ect3 and ect4 single mutant phenotypes is difficult to screen (trichome branching and root slanting for ect2 or ect3, or none detected so far for ect4). Plants co-expressing ECT2-mCherry and DR5:GFP used for fluorescence microscopy were the F1 progeny of a genetic cross between DR5: GFP (Benková et al., 2003) and ECT2-mCherry-expressing plants, performed in the same way as the other crosses described here.

Generation of MTA-FLAG-TFP/ECT2-mCherry transgenic lines

The upstream regulatory elements (1836 nt) followed by the coding sequence of MTA (ATAG10760) and its downstream terminator (709 nt) (MTApro, MTA and MTAter, respectively) were amplified from genomic DNA of Col-0 wildtype inflorescences (DNA extraction was performed as described by Arribas-Hernández et al., 2018) by PCR using USER-compatible primers and the KAPA HiFi Hotstart ReadyMix ReadyMix (Roche). The primers were designed to create overhangs compatible with either the pAc USER cassette present in pCAMBIA2300U [pCAMBIA2300 with a double pAc USER cassette inserted between the PstI-XmaI sites at the multiple cloning site (Nour-Eldin et al., 2006), or with the flanking sequences of a FLAG-TFP double-tag that was amplified from a pCAMBIA3300U-AGO1pro:FLAG-TFP-AGO1-AGO1ter plasmid produced in our laboratory (L-A.-H., unpublished work) using the same USER-compatible methodology. To obtain the MTApro:MTA-FLAG-TFP-MTAter construct, the fragments were combined and introduced into pCAMBIA2300U by USER cloning (Bitinaite and Nichols, 2009). Kanamycin-resistant colonies were analyzed by restriction digestion and sequencing, and Arabidopsis stable transgenic lines were generated by floral dip transformation (Clough and Bent, 1998) of mta-2/+ plants using Agrobacterium tumefaciens GV3101 carrying the pCAMBIA2300U-MTApro:MTA-FLAG-TFP-MTAter plasmid. Selection of primary
transformants (T1) was carried out on MS-agar plates supplemented with kanamycin (50 mg/l). Additionally, plates contained glufoxamine ammonium (Fluka) (7.5 mg/l) to select for the mta-2 allele. Segregation studies and genotyping of T2 populations (see below) grown on MS-Agar plates supplemented with either kanamycin (50 mg/l) or glufoxamine ammonium (7.5 mg/l), and protein blotting of seedling extracts (see below), allowed the isolation of two independent lines with a single T-DNA insertion locus and comparable expression levels of MTA-FLAG-TFP in an mta-2 homozygous background (see Fig. S2). Both lines complemented the embryo-lethality of the null mta-2 mutant and did not exhibit the obvious developmental defects typical of mTA-deficient mutants (Bodi et al., 2012; Rüžička et al., 2017; Shen et al., 2016). T2 plants of the two independent lines were crossed to two independent ect2-1 ECT-2-mCherry lines, and plants in the resulting F1 progeny were used for fluorescence microscopy. Identical patterns of expression were observed for the two different combinations of lines.

**Genotyping**

The method used for genotyping all mutant alleles ECT2, ECT3 and ECT4 is that of Arribas-Hernández et al. (2018). To genotype homozygous mta-2 in lines expressing MTApro:MTA-FLAG-TFP-MTAter, we extracted genomic DNA from young leaves in the same way and used primers LA822-LA823 (wild-type band) and LA269-LA823 (T-DNA band) for PCR (see Fig. S2A). Of note, the reverse primer used to detect the wild-type band (LA823) spans the stop codon of MTA, annealing to the end of its coding sequence and the beginning of its 3’UTR. Accordingly, the primer LA823 does not anneal to the C-terminally tagged MTApro:MTA-FLAG-TFP-MTAter, and therefore it does not detect the wild-type copy of MTA contained in the transgene, allowing for unambiguous genotyping of the mutant background in transgenic lines.

**Western blotting**

Protein extraction from 10-day-old vertically grown seedlings and western blotting with ECT2 and mCherry antibodies were carried out as previously described (Arribas-Hernández et al., 2018), with the only difference being that ECT2 antisera instead of ECT2 antibodies affinity purified against antigenic peptides were used for ECT2 detection (1:500 dilution). For selection of MTApro:MTA-FLAG-TFP-MTAter lines based on MTA-FLAG-TFP protein expression, GFP antisera (Brodersen et al., 2008) were used at 1:30,000 dilution. In all cases, loading is documented by amido black staining of the large subunit of RUBISCO on the same membrane. The plant material was then infiltrated and embedded in Spurr’s resin. The samples were sectioned (2 µm) on a SuperNova Reichert-Jung microtome, stained with 0.05% Toluidine Blue-O (pH 4.4), and imaged with a Nikon Eclipse 80i microscope. Statistical analyses were carried out in two different ways, depending on the data. For the size of the SAM, a linear model with genotype as fixed effect was fitted to the measured data. For the number of epidermal cells in the first true leaves and vascular cells in hypocotyls, a generalized linear model with Poisson distribution was fitted to the data, again using genotype as the fixed effect. This was followed by a post-hoc pairwise comparison of genotypes within DAG or cell type. The doubling time of epidermal cells in the first true leaves was calculated from the slopes of the fits to the corresponding models.

**Macroscopic imaging of plant organs**

Photographs of seedlings, roots, rosettes, detached leaves, flowers, inflorescences and siliques were acquired with a Leica MZ16 F stereomicroscope mounted with a Sony o6000 camera for specimens smaller than 2 cm, or with a Canon EOS 1100 D when larger. The cameras were used both for illustrations and for measurements taken on the acquired images. All plants and plant organs were photographed fresh without further manipulation except for siliques showing the seeds contained inside, which were cleared in 90% acetone at 4°C until transparent.

**Characterization of leaves**

Pictograms of detached leaves were obtained from photographs using the tool ‘Adjust/Threshold’ of the ImageJ software (Schindelin et al., 2012). The area of every leaf (including petiole) was measured with the same software applying ‘Analyze Particles’ to pictograms of the two first pairs of leaves of 8-10 plants for each genotype and time point. All plants were grown in parallel and the same plants were used to quantify the surface of the first and the second pair of leaves, allowing for direct comparison between data displayed on the two different graphs. As the leaves had to be detached to allow quick and accurate quantification of their surfaces, we used a new set of plants for every 2 days- spaced sampling. Thus, negative oscillations in leaf size over time are due to natural variability among plants of the same genotype, rather than to leaf shrinkage. For statistical analyses, a linear model was fitted to the surface area data with days after germination (DAG) and genotype as fixed effects. Variance stabilizing transformation was determined for the response variable (leaf area) using the Box-Cox procedure (Box and Cox, 1964). Post-hoc pairwise comparisons were made between the genotypes for each DAG.

**Characterization of roots**

The characterization and quantification of root growth were made on data points acquired by marking the position of the root tips as they grew vertically on the surface of square MS-agar plates every 24 h from 2 to 11 days after germination. For each graph/plot, only plants grown on the same plates were considered. To characterize mutant alleles, three genotypes were compared at a time. Sterile seeds were spotted 4.2 mm apart from each other on a single row containing three groups of two consecutive seeds per genotype [2×(2×4)=16 seeds per plate], in a total of 10-22 plates. After 11 days of growth, the plates were photographed from the back to obtain sharp images of the daily marks overlaid on the roots. We used the image processing package Fiji (Schindelin et al., 2012) to obtain (x,y) coordinates (in mm) of each mark. The coordinates were re-aligned to match the first mark match the (0,0) origin of coordinates, and plotted on a two-dimensional x/y space (using Excel) overlaying roots of the same genotype. These computer-generated images are mirrors of the
photographs that represent the seedlings as having the camera facing the front side of the open plate (Fig. 4A). The coordinates were also used to calculate growth rate (G[mm/day]), length L[mm] and growth indices (VGI, HGI, HGIh and HGIh). VGI (=Ly/L) and HGI (=Lx/L) were calculated after 11 days of growth as described by Grabov et al. (2005). To better describe horizontal growth, we calculated partial HGIh based on daily increments of growth (for growth between days m and n, HGIh,m-n=G3,m-G3,n), from days 2-3 to days 10-11, sorted the nine values of every root into negative (left) and positive (right) categories, and summed the numerical values in each category to obtain HGIh and HGIh, respectively. For statistical analyses, we conducted one-way ANOVAs to compare the effect of genotypes on the growth indices (VGI, HGI, HGIh, and HGIh). For growth rate, a linear mixed effect model was fitted to the data with DAG and genotype as fixed effects and plant as random effect to account for the repeated measures on the same plants. Variance stabilization transformation was determined for the response variable (growth rate) using the Box-Cox procedure (Box and Cox, 1964). When the ANOVA was significant, a post-hoc pairwise comparison was performed to find pairwise significant differences between genotypes.

Quantification of divergence angles

To describe phyllotactic patterns, the divergence angle between the insertion points of two successive floral pedicels in mature inflorescences was measured as previously described by Peaucelle et al. (2007) using the 16 sectors defined in Fig. 7A, with 0° in the midpoint of interval 1 and the golden angle (137.5) towards the middle of interval 7 (Prasad et al., 2011). To measure, we used the homemade device shown in Fig. S13, inspired by the device described by Peaucelle et al. (2007). Also following Peaucelle’s work, the phyllotactic orientation of each plant was set to the direction giving the smallest average divergence angle. For statistical analysis, we carried out χ² tests of the counts of divergence angles in 17 and in 19 between wild type, te234 and Gte234 (Fig. 7B), or between wild-type and hakai-1, or wild type and ABI3p:MTA/mta-1 (Fig. 7C), and calculated P-values for the resulting 17:19 ratios.

Characterization of flowering time, stem growth and flower morphology

Quantification of DAG plus number of leaves at flowering time and stem length plus days after bolting to produce 10 flowers was carried out manually for 8-20 plants per genotype, accounting for a total of 203 plants in the 20 genotypes assessed (see Figs S10 and S11). A plant was considered to be flowering on the day that the elongating stem was visible, and it was considered to reach the 10-flower day when the 10th flower on the main stem was wide open. For statistical analyses, a one-way ANOVA was conducted to compare the effect of genotypes on the dependent variable (NL, DAG, NLD, SL, DAB and SGD). When the ANOVA was significant, a post-hoc pairwise comparison was performed to find significant differences between genotypes.

Quantification of petal number was carried out manually by counting the number of petals produced by the first 10 flowers on the main shoot of 4-10 plants per genotype, accounting for a total of 1395 flowers from the dataset to fit the model. Proportional odds ordinal regression was carried out with random effect of individual pots, allowing for direct comparison between data displayed on different figure panels. For statistical analyses, we applied a proportional odds model for ordinal regression using the ordinal package in the R software system. The response variable (number of petals) was on an ordinal scale from three to seven petals. Of note, we removed the only three flowers with two petals from the total of 1395 flowers in the dataset to fit the model. Proportional odds ordinal regression was carried out with random effect of plant. The random effect is used to account for the plant-to-plant variation in the pattern of petal numbers, as we counted petals of several different flowers on each of the 10 mature fruits from the main inflorescence stems of 5-10 plants, placed them on stickers (carpets to the sides and replum up/down) and photographed them. Using the software Image J, we quantified the width of the siliques as the length of a line drawn across the fruit perpendicular to the carpel surfaces at the point of maximum thickness (that was the middle point in Col-0 wild type, but was often located towards one end in ect2/ect3 and ect2/ect3/ect4 mutants). Owing to a higher propensity of mutant fruits to bend, we quantified the length of the fruit as the sum of the lengths of two lines, one drawn from one end of the fruit to the point of maximum bent, and another from that point to the other end. As the measurements of silique width displayed heteroscedasticity, we applied a Kruskal–Wallis rank sum test for differences in silique width among genotypes followed by a Wilcoxon signed rank pairwise comparison tests for differences of silique width between genotypes.

Fluorescence microscopy

Roots were imaged with a Zeiss LSM700 confocal microscope in all cases except for the micrographs of ECT2mCherry/MTA-FLAG-TFP co-expressing roots, which were acquired with a Leica SP5-X. To image IMs we also used a Leica SP5-X confocal microscope, equipped in this case with dipping objectives. The only exceptions were the images of IMs expressing ECT2-mCherry in Fig. 5B.C that were taken with a Zeiss LSM780 (also with dipping objectives). mCherry was excited using laser light of 555 nm in Zeiss microscopes, or of 570 nm in Leica SP5-X, and is represented in magenta in all the main figures to aid visualization when combined with green. Venus and GFP were excited with laser light of 488 nm in Zeiss microscopes, and of 510 nm (only Venus) in the Leica platform. TFP was excited using argon laser light of 458 nm (only with the Leica SP5-X microscope). Emitted light was captured by the filter configuration pre-programmed for mCherry, Venus, GFP and TFP on the respective microscope software. Confocal z-section stacks were collected at 0.3 μm spacing throughout the depth of the tissue. 3D and orthogonal projections of z-section stacks and merged images were obtained using Imaged (Schneddelin et al., 2012).

Scanning electron microscopy (SEM)

Scanning electron microscopy was carried out as described by Dong et al. (2019). Briefly, mature fruits were fixed in formaldehyde and infiltrated under vacuum. The materials were critical-point dried in CO2 and spotter coated with gold. The samples were subsequently examined using a Zeiss Supra 55VP field Scanning Electron Microscope with an acceleration voltage of 3.0 kV.

In situ hybridization

Primary and young secondary inflorescences of Col-0 wild-type, ect2-1 and ect3-1 plants were fixed and embedded in Paraplast Plus embedding medium (Sigma), cut at 8 μm and hybridized as described previously (Dreni et al., 2007). The ECT2 and ECT3 digoxigenin-labeled antisense RNA probes (see Fig. SSC for a schematic overview of their locations) were generated by in vitro transcription according to the instructions provided with the DIG RNA labeling kit (SP6/T7, Roche). The templates for the probes, which target the 3’UTR of ECT2 or the coding sequence of ECT3, were obtained from cDNA of Col-0 wild-type inflorescences (obtained as described by Arribas-Hernandez et al., 2018) amplified by PCR with primers LA724-LA725 (ECT2) or LA391-MH35 (ECT3), cloned into TOPO TA (Thermo Fisher Scientific) in anti-sense direction from the T7 promoter contained in the plasmid, and re-amplified with primers LA333(M13) and LA724 (for ECT2) or LA391 (for ECT3). Sections were observed using a Leica DM6000 equipped with differential interference contrast (DIC) optics. Of note, we also designed a probe for ECT4 but it did not produce signal in sections of inflorescences, perhaps due to low ECT4 expression levels.

Acknowledgements

We thank Lena Bjørn Johannson, Philip Andersen and Mathias Tankmar for assistance in the construction of mutants and transgenic lines; Theo Balsterli and his team for plant care; Sarah Rennie and Carlotta Procelli for bioinformatic assistance; Stefano Bencivenga for help with confocal imaging of IMs; and Jonas Riff Larsen for help with statistical analyses.


