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BRUSHY1/TONSOKU/MGOUN3 is required for heat stress memory

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Abstract

Plants encounter biotic and abiotic stresses many times during their life cycle and this limits their productivity. Moderate heat stress (HS) primes a plant to survive higher temperatures that are lethal in the naïve state. Once temperature stress subsides, the memory of the priming event is actively retained for several days preparing the plant to better cope with recurring HS. Recently, chromatin regulation at different levels has been implicated in HS memory. Here, we report that the chromatin protein BRUSHY1 (*BRU1*)/TONSOKU/MGOUN3 plays a role in the HS memory in *Arabidopsis thaliana*. *BRU1* is also involved in transcriptional gene silencing and DNA damage repair. This corresponds with the functions of its mammalian orthologue TONSOKU-LIKE/NFKBIL2. During HS memory, *BRU1* is required to maintain sustained induction of HS memory-associated genes, whereas it is dispensable for the acquisition of thermotolerance. In summary, we report that *BRU1* is required for HS memory in *A. thaliana*, and propose a model where *BRU1* mediates the epigenetic inheritance of chromatin states across DNA replication and cell division.

KEYWORDS

Arabidopsis thaliana, *BRU1*, chromatin, priming

1 | INTRODUCTION

As sessile organisms, plants are frequently exposed to environmental conditions that are stressful in the sense that they interfere with their optimal growth and development. Such extreme environmental conditions are likely to increase in frequency and severity with climate change (Battisti & Naylor, 2009; Lobell, Schlenker, & Costa-Roberts, 2011). In recent years, it has become increasingly clear that plants can be primed by stress exposure and that this enhances their response to a second stress exposure, which may be qualitatively the same or different, after a stress-free period (Bruce, Matthes, Napier, & Pickett, 2007; Conrath, Beckers, Langenbach, & Jaskiewicz, 2015; Hilker et al., 2016). The molecular basis of priming and memory is still not well understood (Lämke & Bäurle, 2017). However, evidence is emerging that priming of stress-induced gene expression is a crucial component of stress priming that is at least in part mediated by epigenetic regulation. Indeed, several studies indicate that chromatin organization and modifications distinguish genes in

the primed state from those in the naïve state (Brzezinka et al., 2016; Ding, Fromm, & Avramova, 2012; Lämke, Brzezinka, Altmann, & Bäurle, 2016; Mozgova et al., 2015). In dividing tissues, this process involves the inheritance of the primed state across DNA replication and cell division. How this is mediated remains unclear.

Due to the high economic relevance and recurring nature of heat stress (HS), both acute responses and longer term responses including priming and memory have been investigated (Bäurle, 2016; Lämke & Bäurle, 2017; Ohama, Sato, Shinozaki, & Yamaguchi-Shinozaki, 2017). The immediate responses to HS have been intensively studied in all kingdoms; a conserved core module, collectively referred to as the heat shock response (HSR; Richter, Haslbeck, & Buchner, 2010), comprises the rapid activation of heat shock transcription factors (HSFs) that in turn induce the expression of heat shock proteins (HSPs), which act as chaperones and prevent or repair protein damage (Akerfelt, Morimoto, & Sistonen, 2010; Ankar & Sistonen, 2011). In plants, the HSR results in the acquisition of thermotolerance and is mediated by a subset of the strongly radiated HSF family (Ohama

et al., 2017; Scharf, Berberich, Ebersberger, & Nover, 2012; Yeh, Kaplinsky, Hu, & Charng, 2012). In *Arabidopsis thaliana*, seven of the 21 HSF genes have been implicated in the acquisition of thermotolerance, among them, three HSF1 isoforms that act as master regulators of the HSR (Ikeda, Mitsuda, & Ohme-Takagi, 2011; Liu, Liao, & Charng, 2011; Mishra et al., 2002; Scharf et al., 2012; Schramm et al., 2008; Yeh et al., 2012; Yoshida et al., 2011).

Notably, at the physiological level, HS primes a plant to subsequently withstand a stronger HS even after a lag phase of 3 days at normal growth temperatures (Charng et al., 2007; Charng, Liu, Liu, Hsu, & Ko, 2006). This process is called maintenance of acquired thermotolerance or HS memory and is an active process that is genetically separable from the acquisition of thermotolerance, as evidenced by a (growing) list of mutants that are specifically defective in the maintenance rather than the acquisition of thermotolerance (Brzezinka et al., 2016; Charng et al., 2006; Charng et al., 2007; Stief et al., 2014).

HS memory requires *HSFA2*, which is so far the only *HSF* gene in *A. thaliana* that functions specifically in HS memory (Charng et al., 2007). *HSFA2* expression is induced by HSF1 isoforms, and *HSFA2* prolongs and amplifies the HS-induction at a subset of HSF1-target genes (Charng et al., 2007; Lämke et al., 2016; Liu et al., 2011; Nishizawa-Yokoi et al., 2011). The target genes of *HSFA2* are enriched in genes that show sustained activation of gene expression after HS; after a short HS pulse, these genes remain induced for 2 to 3 days, and although their initial induction is not changed in *hsfa2* mutants, their transcriptional activity declines faster in *hsfa2* mutants (Lämke et al., 2016; Stief et al., 2014). Interestingly, *HSFA2* binds transiently to memory-gene loci and presumably recruits sustained chromatin modifications, in particular the hyper-methylation of histone H3K4 (Lämke et al., 2016). This hyper-methylation correlates closely with the duration of the memory period. A second link between HS memory and chromatin organization has been reported through the finding that the *FORGETTER1* gene is required for sustained induction of *HSA32* and other memory genes after HS (Brzezinka et al., 2016). *FORGETTER1* is a highly conserved helicase-domain protein that maintains low nucleosome occupancy throughout the memory phase through the interaction with chromatin remodelers of the SWI/SNF and ISWI classes (Brzezinka et al., 2016; Farrona, Hurtado, Bowman, & Reyes, 2004; Li et al., 2014). Taken together, the current model is that the sustained induction of HS memory-associated genes is mediated through chromatin modifications and involves both nucleosome occupancy and posttranslational modification of nucleosomes. As the sustained induction of gene expression is maintained for several days, an interesting question is whether and how the primed chromatin states are inherited through DNA replication and cell division.

Chromatin regulation also plays an important role in the regulation of somatic stress memory in response to other biotic and abiotic stresses (Bruce et al., 2007; Hilker et al., 2016; Lämke & Bäurle, 2017; Sani, Herzyk, Perrella, Colot, & Amtmann, 2013; Vriet, Hennig, & Laloi, 2015). In particular, histone H3K4 hyper-methylation has been implicated in stress memory after dehydration and pathogen infection (Ding et al., 2012; Feng et al., 2016; Jaskiewicz, Conrath, & Peterhänzel, 2011; Kim et al., 2012; Singh et al., 2014). The regulation of nucleosome occupancy was implicated in the priming of defence genes (Mozgova et al., 2015).

The *BRUSHY1 (BRU1)/TONSOKU/MGOUN3* gene was originally identified based on its fasciated stems and loss of transcriptional silencing (Guyomarc'h, Vernoux, Traas, Zhou, & Delarue, 2004; Suzuki et al., 2004; Takeda et al., 2004). It encodes a nuclear protein with tetratricopeptide-repeat and leucine-rich repeats protein interaction domains. *Bru1* mutant plants have disorganized meristems due to altered *WUSCHEL* expression, and the stems tend to enlarge and separate into multiple stems (fasciation; Guyomarc'h et al., 2004; Suzuki et al., 2004). As *bru1* is hypersensitive to DNA damage, it was also suggested that *BRU1* is involved in DNA damage repair pathways (Takeda et al., 2004). Because mutants in Chromatin assembly factor (CAF-1) components (*FASCIATA1 [FAS1]* and *FAS2*) have similar phenotypes with respect to both developmental aspects and DNA damage hyper-sensitivity, it was suggested that *BRU1* has a similar function (Takeda et al., 2004). CAF-1 deposits H3 and H4 into newly assembling nucleosomes after DNA replication and repair (Probst, Dunleavy, & Almouzni, 2009; Smith & Stillman, 1989). Thus, *BRU1* was proposed to function in the epigenetic inheritance of chromatin states. This is in line with the observation that in synchronized cell cultures, *BRU1* expression peaks during S-phase (Suzuki et al., 2005).

More recently, a *BRU1* orthologue was identified in mammals and named TONSOKU-LIKE (TONSL)/NFKBIL (Duro et al., 2010; O'Connell et al., 2010; O'Donnell et al., 2010). TONSL interacts with MMS2L and is involved in DNA repair, where the complex binds to single-stranded DNA and facilitates loading of RAD51 (Huang et al., 2018). TONSL also regulates DNA replication and acts as a H3-H4 histone chaperone (Campos et al., 2015; Piwko et al., 2010). Interestingly, a connection to the epigenetic inheritance of chromatin modifications remains elusive, although the Ankyrin repeat domain of TONSL acts as a histone reader domain (Saredi et al., 2016).

Here, we report that *BRU1* is required for the memory of HS. We show that *BRU1* is required for sustained activation of HS memory-associated genes and that this occurs at the transcriptional level. The moderate HS used in this study induced only very low amounts of cell death and did not induce the expression of DNA damage marker genes *RAD51* and *PARP2*. Neither cell death nor DNA damage marker gene expression is increased in *bru1*, indicating that the DNA damage hyper-sensitivity is unlikely to be responsible for the HS memory defects. In addition, the acquisition of thermotolerance is not affected in *bru1*, and mutants in CAF-1 do not display a HS memory defect. The effect on memory-gene expression is confirmed by our global transcriptome analysis. In summary, we find that *BRU1* is specifically required for HS memory and propose a model where *BRU1* acts in the inheritance of chromatin-based memory components through chromatin reassembly that is necessitated by nucleosome turnover and DNA replication.

2 | MATERIALS AND METHODS

2.1 | Plant materials and growth conditions

Seedlings of the Col-0 or Wassilewskaja (Ws) backgrounds were germinated on GM medium (1% (w/v) glucose) under a 16/8 hr light/

dark cycle at 23/21°C. The *hsa32* and *hsp101* were described previously (Stief et al., 2014). *Bru1-1* (Ws) and *BRU1::BRU1-GFP* in *bru1-1* background were obtained from S. Takeda (Ohno et al., 2011). *Bru1-2*, *bru1-4* (N534207; Takeda et al., 2004), *fas1-4* (SAIL662_D10), and *fas2-4* (N533228, both; Exner, Taranto, Schonrock, Gruissem, & Hennig, 2006) were obtained from the Nottingham Arabidopsis Stock Centre.

2.2 | Thermotolerance assays

Heat treatments were performed on 4-day-old seedlings. Seedlings were treated with an acclimatizing HS (ACC) of 37°C, followed by 90 min at room temperature, and by 45 min at 44°C, starting 8 hr after light onset. As tester HS, a 44°C treatment for the indicated duration was applied at the indicated number of days after ACC. After HS, plants were returned to normal growth conditions until analysis. Acquisition of thermotolerance and basal thermotolerance were assayed as described (Stief et al., 2014). For all thermotolerance assays, all genotypes of one treatment were grown on the same plate.

2.3 | Gene expression analysis

Transcript levels were quantified by qRT-PCR analysis as described previously (Brzezinka et al., 2016; Stief et al., 2014). In brief, total RNA from flash-frozen seedlings was extracted using the Hot Phenol method, residual DNA was removed using Turbo DNase (Ambion) and the RNA was reverse transcribed using oligo-dT primers and SuperScript III (Invitrogen). Quantitative PCR was performed on 1:20 diluted cDNA using GoTaq SybrGreen qPCR Master Mix (Promega). Oligonucleotide sequences are listed in Table S1. Transcript levels were quantified using the $\Delta\Delta C_t$ method. Transcript levels were normalized to the reference genes *TUB6* or *At4g26410* (Czechowski, Stitt, Altmann, Udvardi, & Scheible, 2005).

2.4 | Trypan blue staining for cell death

Trypan blue staining was performed 96 hr after ACC treatment as described (Inagaki, Nakamura, & Morikami, 2009). In brief, seedlings were incubated in 0.5 mg/ml Trypan blue, dissolved in phenol/glycerol/lactic acid/water/ethanol (1:1:1:1:8), in a boiling water bath for 1 min. The tissues were left in staining solution at room temperature for 1 hr, cleared in chloral hydrate solution, and examined with a Leica stereomicroscope.

2.5 | Microscopy

GFP fluorescence was imaged using a Zeiss LSM710 confocal microscope.

2.6 | Microarray analysis

For microarray hybridization, 4-day-old seedlings of *Col-0* or *bru1-2* were either treated with ACC (see above) and harvested 4 or 52 hr after the end of the treatment (three biological replicates). As control, No-HS samples (three biological replicates) were harvested together

with the 4 hr ACC samples. The *bru1-2* samples described here were part of a larger experiment reported previously, in which the *Col-0* samples were already described (Stief et al., 2014). RNA extraction, probe preparation, and hybridization of Affymetrix GeneChip ATH1 microarrays and their analysis was described previously (Stief et al., 2014). The clustered heat map analysis was performed using Heatmapper (Babicki et al., 2016) with settings value, average linkage, and Euclidean distance. The microarray data are deposited as GSE83136 and GSE112161.

3 | RESULTS

3.1 | BRU1 is specifically required for HS memory

From a reverse genetic screen, we identified *bru1-2* as a mutant with impaired HS memory. Four-day-old seedlings were treated with a two-step acclimation treatment (consisting of 1 hr at 37°C and then 45 min at 44°C, see Section 2 for details), which was followed by a 2-day period at standard growth temperatures, and then a tester HS that is lethal to a plant that has not been acclimated (Figure 1a; Stief et al., 2014). As a control, we included the *hsa32* mutant that was previously shown to have a defective HS memory (Charng et al., 2006). *Bru1-2* mutants displayed reduced growth and survival after the second HS relative to the wild type *Col-0* control (Figure 1a). We next confirmed that the basal thermotolerance (i.e., the level of HS at 44°C that a not-acclimatized plant can survive) and the acquired thermotolerance (i.e., the level of HS at 44°C that a plant can survive after acclimation for 1 hr at 37°C) were not affected in *bru1-2* mutants (Figure S1). Together, this indicates that *bru1-2* mutants are specifically defective in the long-term, but not the acute HS responses.

3.2 | BRU1 mediates sustained transcriptional induction of HSA32 after HS

To begin to investigate the molecular basis of this loss-of-memory phenotype, we next analysed the expression of *HSA32* in *bru1-2* mutants. *HSA32* is essential for HS memory in *A. thaliana* (Charng et al., 2006) and is highly induced by HS. Interestingly, induction of *HSA32* is sustained over 3 days following the ACC treatment (Charng et al., 2006; Stief et al., 2014), and thus the expression pattern correlates well with HS memory. We profiled transcript levels of acclimated plants at the end of the ACC treatment and during a 3-day recovery phase. Similar to the *Col-0* wild type, *bru1-2* mutants displayed high induction of *HSA32* and sustained high expression levels during the first day of recovery (Figure 1b). However, *bru1-2* thereafter displayed a stronger decline of *HSA32* expression compared with wild type, consistent with a role in HS memory.

The sustained induction of *HSA32* after ACC occurs at the transcriptional level, as was previously found by the quantification of unspliced transcripts (Brzezinka et al., 2016). Because splicing occurs in close proximity to transcription, quantifying unspliced transcript levels is used as a proxy for transcriptional activity (Bäurle, Smith, Baulcombe, & Dean, 2007; Stief et al., 2014). Unspliced *HSA32* transcript levels in *bru1-2* were similar to *Col-0* until 24 hr after ACC, but thereafter declined faster (Figure 1c), thus

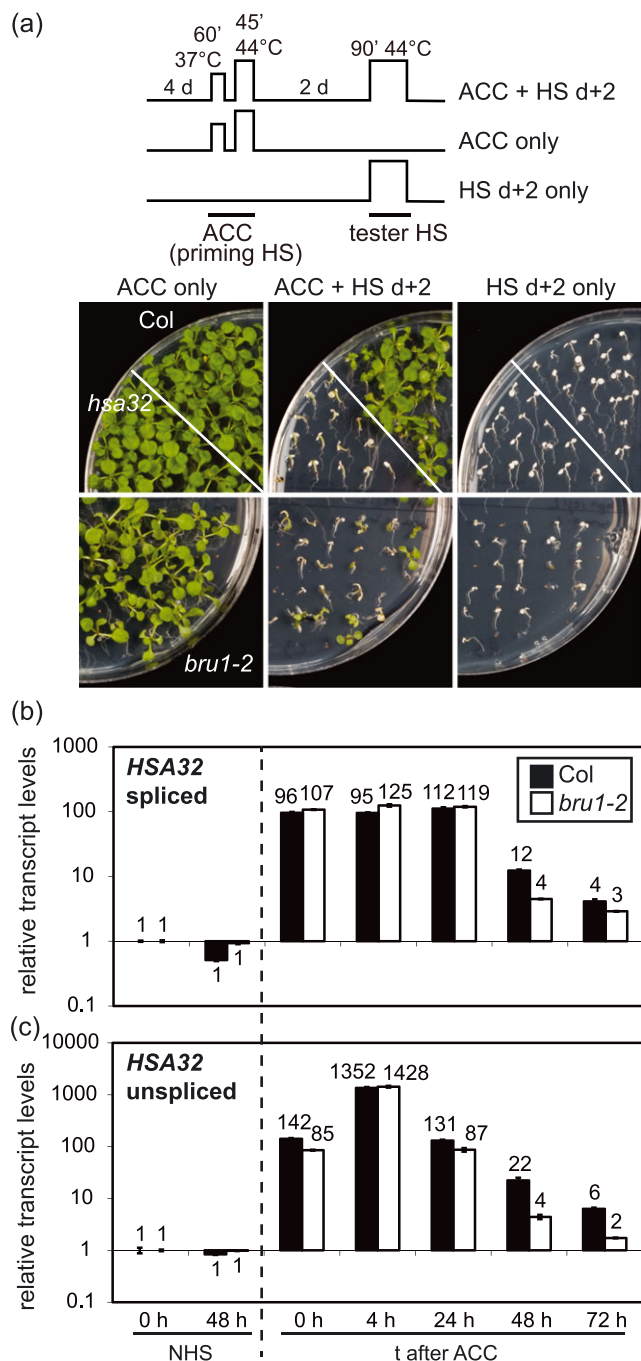


FIGURE 1 *BRU1* is specifically required for heat stress (HS) memory and sustained transcriptional induction of *HSA32* after HS. (a) *Bru1-2* mutants are impaired in HS memory at the physiological level. Four-day-old seedlings of the indicated genotypes were subjected to acclimatizing HS (ACC) treatment; 2 days later, they were exposed to a tester HS at 44°C for 90 min. All genotypes were grown on the same plate. Photographs were taken 14 days after ACC. One representative of more than three independent experiments is shown. (b,c) Transcript levels of spliced (b) and unspliced (c) *HSA32* were analysed by quantitative RT-PCR in Col-0 and *bru1-2* at the indicated time points after the end of ACC or in no-HS controls (NHS) harvested at corresponding time points. Expression values were normalized to *TUB6* and to 0 hr NHS. Data are averages of three biological replicates \pm SEM. Data are plotted on a \log_{10} scale

confirming the results for the spliced *HSA32* transcripts and indicating that *BRU1* acts to sustain induction of *HSA32* at the transcriptional level.

3.2.1 | *Bru1* mutants are not generally hyper-sensitive to HS

BRU1 has been previously implicated in DNA damage repair and *bru1* mutants are hyper-sensitive to DNA damage, resulting in increased cell death (Takeda et al., 2004). Thus, we tested whether the HS memory defect in *bru1-2* could be ascribed to this hyper-sensitivity. To this end, we first tested whether ACC increased cell death in *bru1-2* cotyledons using Trypan blue staining. This staining visualizes individual dead cells within tissues. Under no-HS conditions, we did not observe any lesions in Col-0 and only very few in *bru1-2* (Figure 2). After ACC, the proportion of wild type seedlings that showed individual dead cells on their cotyledons increase to 39% (Figure 2). In contrast, only 18% of *bru1-2* seedlings displayed lesions on their cotyledons, indicating that the ACC treatment does not induce increased cell death in *bru1-2* compared with Col-0.

BRU1 has also been implicated in cell cycle control; *BRU1* is expressed during the S-phase of the cell cycle and its loss delays cell cycle progression (Suzuki et al., 2005). To estimate cell division dynamics after ACC, we assayed the expression levels of histone H4, whose expression is limited to the S-phase. In wild type, histone H4 transcript levels were roughly halved after ACC and remained slightly reduced during the 3-day recovery period that was assayed. In *bru1-2* mutants, histone H4 transcript levels in nonstressed seedlings were roughly halved compared with Col-0 (Figure 3), confirming a general reduction in cell cycle progression (Suzuki et al., 2005). In contrast to wild type, H4 transcript levels in *bru1-2* were not further reduced after HS (Figure 3).

Consistent with a role in DNA damage repair, it was previously reported that the DNA damage marker *PARP2* was hyper-induced in *bru1-2* mutants (Takeda et al., 2004). Thus, we were interested to test whether ACC (further) induced the expression level of the DNA damage markers *RAD51* and *PARP2* (Breuer et al., 2007). Interestingly, neither gene displayed increased expression levels in *bru1-2* under our no-HS conditions. After HS, *RAD51* and *PARP2* transcript levels did not change in wild type (Figure 3). The same was true for *bru1-2* mutants. Together, our findings indicate that the ACC treatment, which is a moderate HS, does not induce ectopic DNA damage or sustained repression of cell division. Moreover, they indicate that DNA damage responses that are mediated by *RAD51* and/or *PARP2* are not ectopically triggered by our NHS growth conditions or by the ACC treatment in *bru1-2*. This corroborates the idea that *BRU1* has a specific function in sustaining HS memory gene expression, and that the observed HS memory defects are not caused by a generic HS hyper-sensitivity.

3.3 | *FAS1* and *FAS2* are not required for HS memory

Mutants in two subunits of the histone chaperone CAF-1 in *A. thaliana*, *fas1* and *fas2*, have similar developmental phenotypes as *bru1*, such as fasciated stems (Kaya et al., 2001), and the mammalian orthologues of *BRU1* and CAF-1 interact functionally (Huang et al., 2018). To test whether CAF-1 is also required for HS memory, we tested mutants in the *FAS1* and *FAS2* subunits for their ability to maintain acquired thermotolerance with the assay described above (Figure 4). In contrast to *bru1-2* and *bru1-4*, the loss-of-function mutants *fas1-4* and *fas2-4* displayed normal HS memory. This indicates that *BRU1* function

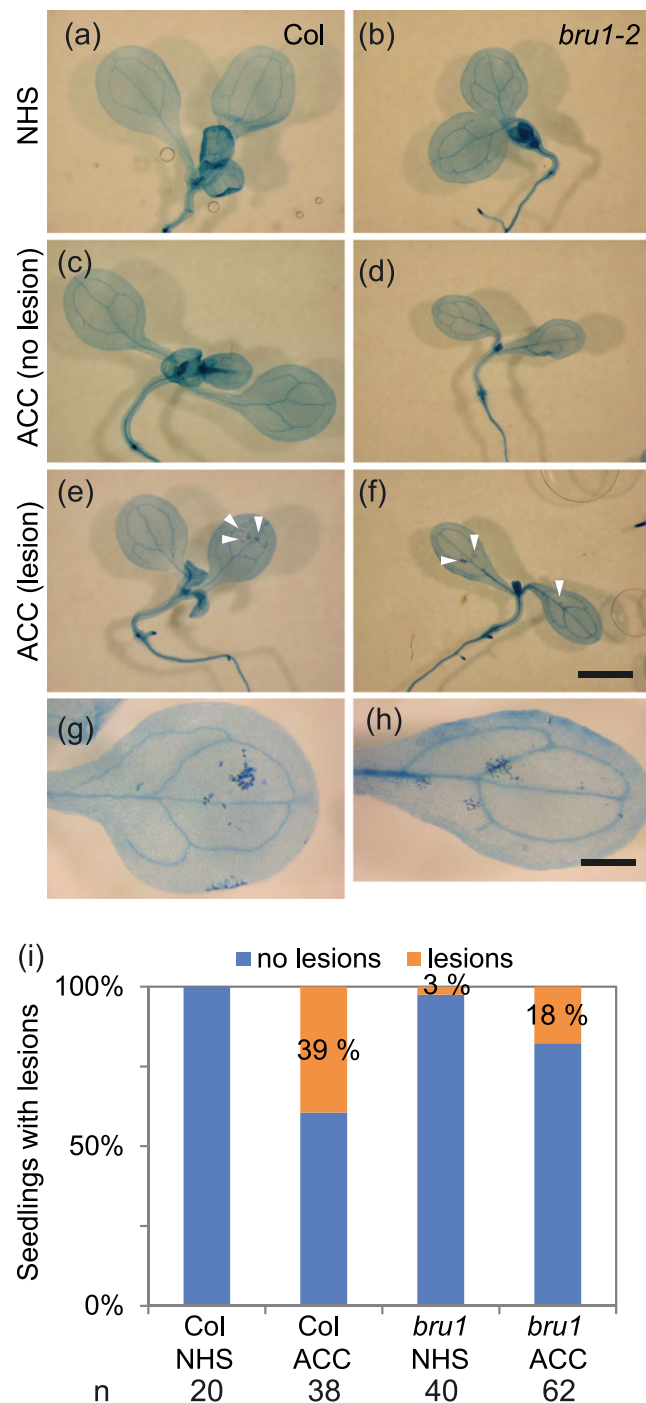


FIGURE 2 Cell death after ACC treatment is not increased in *bru1-2* mutants relative to Col-0 wild type. (a–h) Cell death was assessed by Trypan blue staining of 4-day-old seedlings of Col-0 (a,c,e,g) and *bru1-2* (b,d,f,h) that were treated with ACC (cf. Figure 1a); 96 hr after the end of ACC, mock- (a,b) or ACC-treated (c–h) seedlings were stained with Trypan blue to visualize cell death and examined under a Leica Stereomicroscope. (g,h) Close-ups of representative cotyledons with lesions. Size bars: 5 mm (a–f), 1 mm (g,h). (i) Percentage of seedlings with lesions of the indicated genotypes and treatments shown in (a–h). n indicates the number of seedlings that were scored for the analysis. ACC: acclimatizing HS; NHS: no-HS controls; HS: heat stress

during HS memory is independent of CAF-1 and that the common developmental aberrations of the mutants do not cause the phenotype.

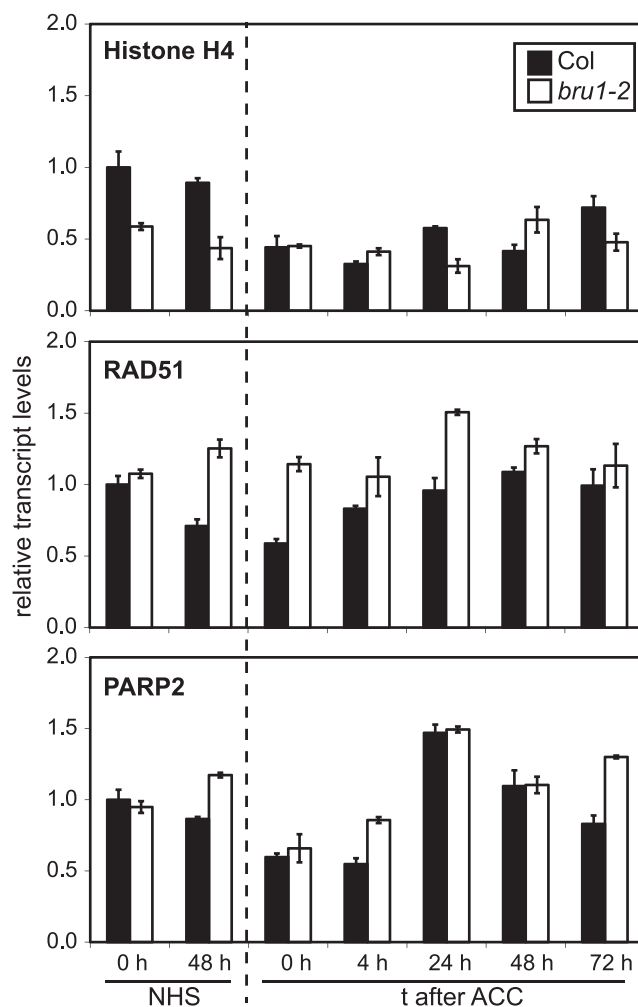


FIGURE 3 Transcript levels of DNA damage marker genes and histone H4 in *bru1-2*. Transcript levels of histone H4, *RAD51*, and *PARP2* were analysed by quantitative RT-PCR in Col-0 and *bru1-2* at the indicated time points after the end of ACC or in no-HS controls (NHS). Expression values were normalized to *TUB6* and Col-0 0 hr NHS. Data are averages of three biological replicates \pm SEM. ACC: acclimatizing HS; HS: heat stress

3.4 | *BRU1* is required for sustained activation of HS memory genes

To confirm that the mutation in *BRU1* was responsible for the phenotype observed in *bru1-2*, we tested two additional alleles, *bru1-4* (in the Col-0 background; Figure 4) and *bru1-1* (in the Ws background; Figure 5a; Ohno et al., 2011; Suzuki et al., 2004; Takeda et al., 2004). Both alleles showed a similar phenotype as *bru1-2* in the HS memory assay. Moreover, reintroduction of a functional *BRU1* copy (*pBRU1::BRU1-GFP*) into *bru1-1* (Ohno et al., 2011) complemented the HS memory defects (Figure 5a). We also confirmed nuclear expression of the *BRU1-GFP* transgene (Figure 5b,c).

Besides *HSA32*, a number of other genes display sustained activation after ACC and are together referred to as HS memory genes (Brzezinka et al., 2016; Charng et al., 2006; Charng et al., 2007; Stief et al., 2014). To analyse whether *BRU1* affects expression of other memory genes besides *HSA32*, we analysed their transcript levels during a 3-day recovery phase after ACC. We investigated transcript levels of the HS memory-associated genes *APX2*, *HSA32*, *HSP22.0*,

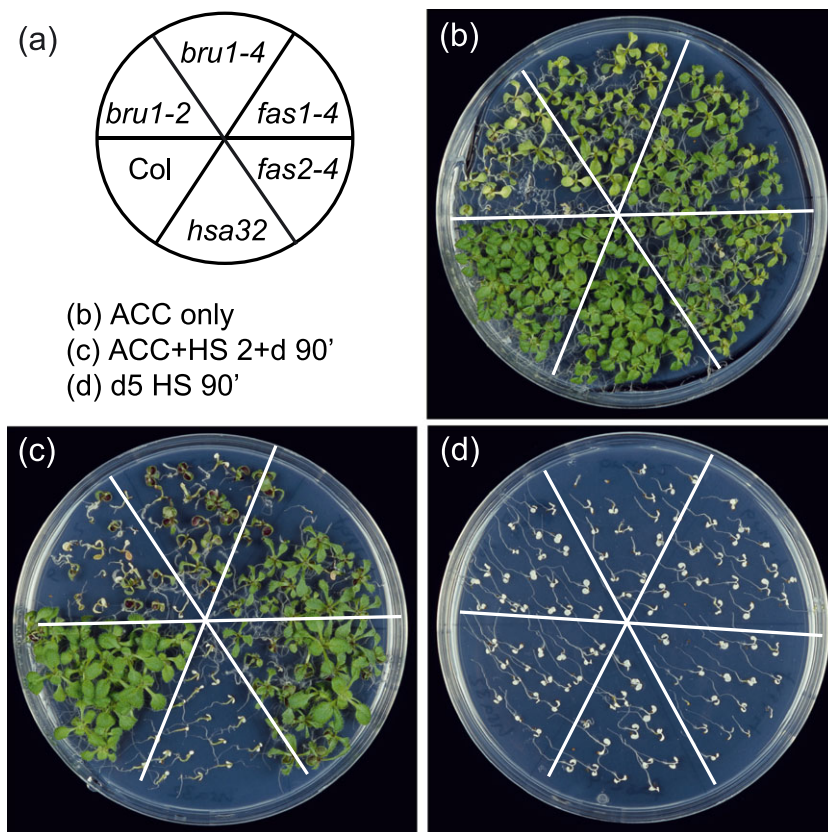


FIGURE 4 The *FAS1* and *FAS2* genes are dispensable for heat stress (HS) memory. (a–d) Four-day-old seedlings of the indicated genotypes (a) were subjected to acclimatizing HS (ACC) treatment; 2 days later, they were exposed to a tester HS at 44°C for 90 min (c). The control plates were either exposed to ACC only (b) or to the tester HS only (d). For each treatment, all genotypes were grown and treated on the same plate. Photographs were taken 14 days after ACC. One representative of several independent experiments is shown

and *HSP21* (Lämke et al., 2016; Stief et al., 2014), as well as the putative upstream regulator *HSFA2* (Charng et al., 2007; Lämke et al., 2016; Nishizawa et al., 2006), and the HS-inducible non-memory gene *HSP101* (Hong & Vierling, 2000) in the *Ws* wild type, *bru1-1* and the complementation line. For *HSP101*, no significant difference was found in *bru1-1* relative to *Ws* (Figure 6). For *HSFA2*, we observed a slightly reduced induction at 0 and 4 hr after ACC in *bru1-1*, but later no significant difference relative to the *Ws* control. In contrast, for *APX2*, *HSA32*, *HSP22.0*, and *HSP21*, induction after ACC was more highly sustained in *Ws* wild type between 28 and 76 hr after ACC relative to *HSP101* and *HSFA2*. However, in *bru1-1*, the expression started to decrease already between 4 and 28 hr and declined significantly faster than in either *Ws* or the complemented line. This indicates that *BRU1* is widely required for sustained activation of HS memory-associated genes, but it is dispensable for the initial activation of these genes.

3.5 | Global transcriptome analysis indicates that *BRU1*-dependent genes are enriched among HS memory genes

We next sought to investigate the requirement of *BRU1* for HS-dependent gene expression at the global level. To this end, we performed transcriptome analysis using ATH1 microarray technology on Col-0 wild type and *bru1-2* seedlings sampled at either 4 or 52 hr after ACC, and a no-HS control that was sampled together with the 4-hr time point (Stief et al., 2014). We first identified ACC-responsive genes (based on $\log_2FC \geq 2$ or ≤ -2 and FDR corrected $P < 0.05$) in Col-0 for either ACC time point relative to NHS (Stief et al., 2014). Figure 7a displays a clustered heat map analysis of the \log_2FC changes

of these genes in Col-0 and *bru1-2* relative to the NHS control. Overall, the data cluster by treatment rather than genotype indicating that treatment-specific effects outweigh genotype effects. Moreover, the genotype differences at 52 hr appear more pronounced than at 4 hr (see below for a more detailed analysis). We next investigated the expression correlation at either time point for the genes that are significantly changed in Col-0. At 4 hr, genes that are upregulated in Col-0 tend to be more strongly upregulated in *bru1-2*, whereas downregulated genes seem to be less strongly downregulated (Figure 7b). In contrast, at 52 hr genes that are upregulated in Col-0 tend to be upregulated less strongly or not at all in *bru1-2* and downregulated genes are less strongly or not at all downregulated in *bru1-2*. Thus, the response at 52 hr is dampened in *bru1-2*. These findings confirm the hypothesis that *bru1-2* mutants have a reduced HS memory response. This was next quantified in Figure 7c; the three classes of genes that are differentially expressed in Col-0 at 4 hr ACC or 52 hr ACC relative to NHS (4 hr only, 4 and 52 hr, 52 hr only) are all enriched in genes that are differentially expressed in *bru1-2* versus Col-0 (ACC/NHS_{*bru1-2*} at least two-fold different from ACC/NHS_{Col-0}) compared with the whole genome (8–75% vs. 1% of all other genes). More specifically, more than half of the genes that are upregulated in Col-0 ACC versus NHS at 52 hr only (54%), and more than half of the genes that are downregulated at either both time points (75%) or 52 hr only (60%), are differentially expressed in *bru1-2* compared with the corresponding Col-0 time point. The genes that are differentially expressed in *bru1-2* under control conditions are listed in Data S1. In summary, *BRU1* is required for the correct expression of HS-responsive genes at a global level. Notably, both upregulated and downregulated genes were strongly affected at 52 hr and for both groups, the differential expression in *bru1-2* was dampened (Figure 7

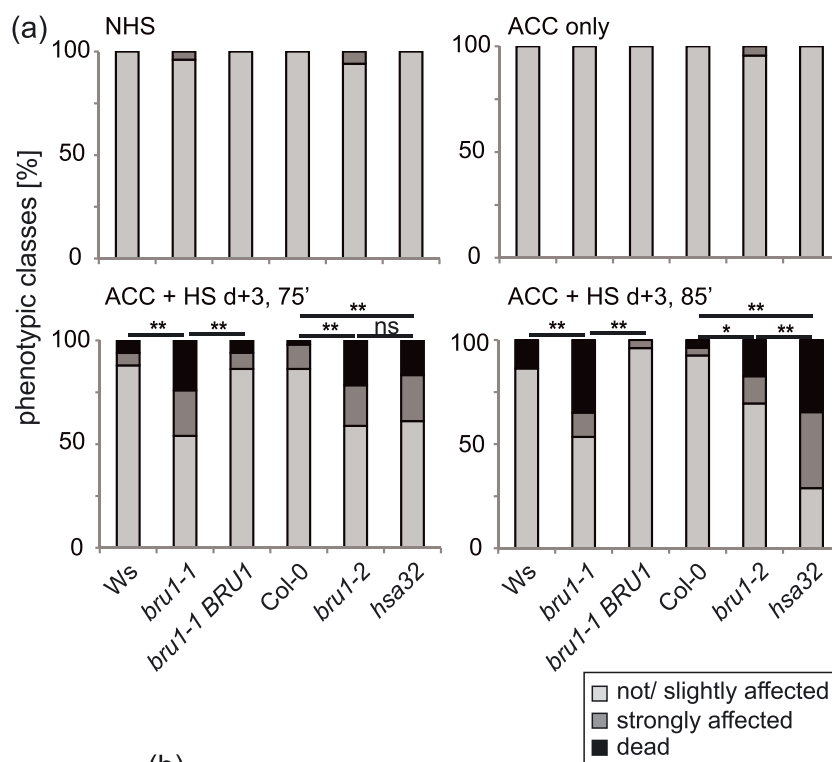


FIGURE 5 Complementation of *bru1-1* with a *pBRU1::BRU1-GFP* construct. (a) *BRU1-GFP* expressed from *pBRU1::BRU1-GFP* complements the HS memory defect of *bru1-1*. Four-day-old seedlings of the indicated genotypes were subjected to ACC treatment; 3 days later, they were exposed to a tester HS at 44°C for the indicated times. Photographs were taken 14 days after ACC (Figure S2) and seedling survival was quantified as described previously (Brzezinka et al., 2016). *, $P < 0.05$; **, $P < 0.01$, Fisher's exact test. Data shown are averages of at least two independent biological replicates each containing at least 43 individuals per genotype. (b) *BRU1-GFP* expressed from *pUBC10::BRU1-GFP* is localized to the nucleus of transiently transformed *Arabidopsis thaliana* protoplasts. The GFP signal is shown in green, chlorophyll autofluorescence is shown in blue. (c) *BRU1-GFP* expressed from *pBRU1::BRU1-GFP* is localized to the nucleus in the roots of stably transformed *A. thaliana*. The GFP signal is shown in green. ACC: acclimatizing HS; HS: heat stress; Ws: Wassilewskaja

b). This trend was not observed for the genes upregulated at 4 hr, corroborating the idea that *BRU1* is mostly required for the memory phase rather than for acute HS responses.

4 | DISCUSSION

Here, we have identified a role for the chromatin-regulatory protein *BRU1* during HS memory in *A. thaliana*. Interestingly, *BRU1* is not required for the acquisition of thermotolerance or basal thermotolerance, and it is dispensable for early HS responses and for the initial HS gene activation. At the molecular level, *BRU1* is required to maintain high levels of expression in HS memory-associated genes throughout the memory phase. Globally, it is also required for

sustained repression after HS as revealed by the transcriptome analysis. Our observations are in line with the previously established functions of *BRU1* (see below).

BRU1 has been implicated in the epigenetic inheritance of transcriptional silencing and in the DNA damage response (Suzuki et al., 2004; Takeda et al., 2004). In addition, it has very similar phenotypes as the histone chaperone CAF-1 (Takeda et al., 2004). Together, this has led to a model where *BRU1* ensures faithful inheritance of chromatin states across DNA replication and cell division. Recent mechanistic work from the mammalian field indicates that TONSL, the *BRU1* orthologue, directly binds to single-stranded DNA during DNA damage repair and recruits RAD51 (Huang et al., 2018). In addition, TONSL regulates DNA replication and binds to newly incorporated nucleosomes after replication (Saredi et al., 2016). In summary, these

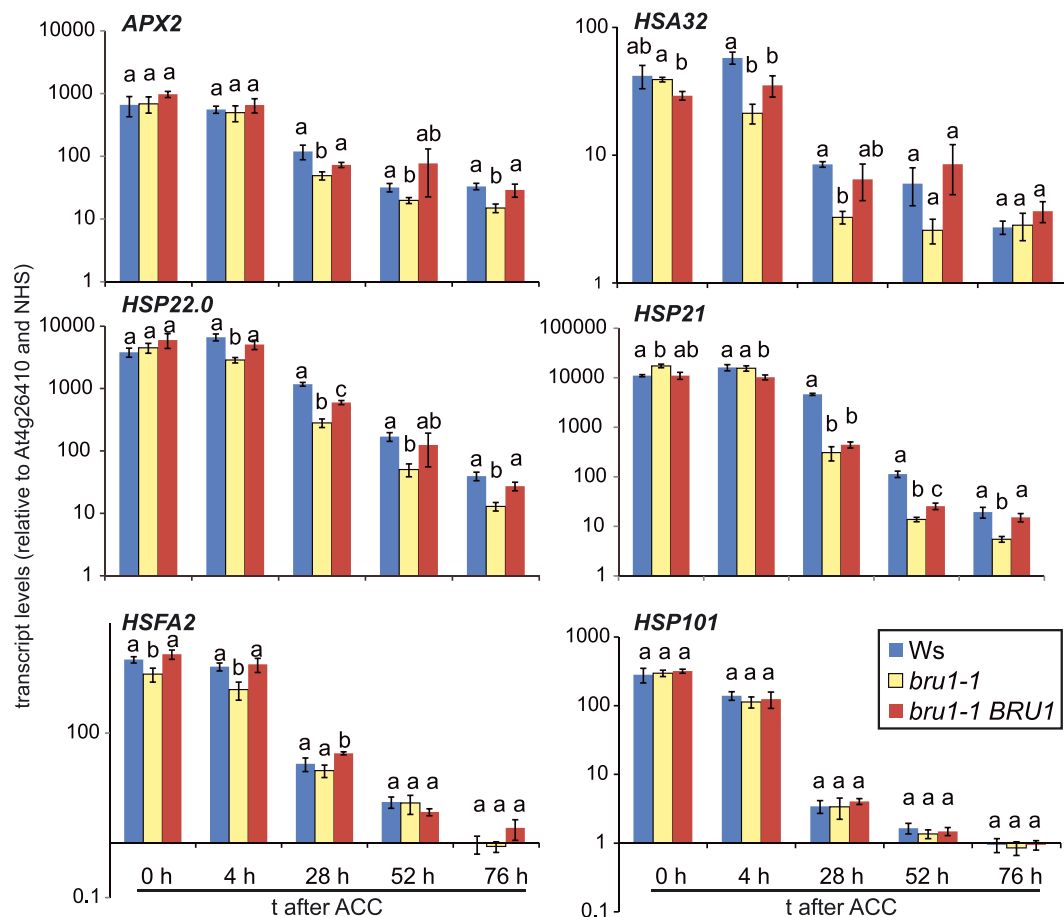


FIGURE 6 Sustained induction of several memory genes after acclimatizing HS (ACC) is impaired in *bru1-1*. Expression profiles of heat stress (HS) memory-associated genes (*APX2*, *HSA32*, *HSP22.0*, *HSP21*), *HSFA2*, and a HS-inducible nonmemory gene (*HSP101*) after ACC in Wassilewskaja (Ws) wild type, *bru1-1* mutants and the complementation line. Transcript levels determined by qRT-PCR were normalized to the *At4g26410* reference gene and the respective NHS control harvested at the same time point. At each time point different letters (a–c) indicate significant differences between the tested genotypes ($P < 0.05$, Student's *t* test), whereas the same letter indicates that there was no significant difference detected. Data represent averages of at least three biological replicates \pm SEM

findings are consistent with the idea that the conserved function of *BRU1* may be not only in DNA damage repair, but also in the faithful inheritance of chromatin states after replication.

The requirement of the chromatin regulator *BRU1* for HS memory strengthens the observation that chromatin structure and organization are important for sustained gene expression during HS memory. Previously, hyper-methylation of histone H3K4 was implicated in this process (Lämke et al., 2016). Histone H3K4 hyper-methylation was also implicated in somatic stress memory after drought stress, salt stress, and pathogen infection (Ding et al., 2012; Feng et al., 2016; Jaskiewicz et al., 2011), as well as in priming phenomena in metazoans and yeast (D'Urso et al., 2016; D'Urso & Brickner, 2014; Guenther, Levine, Boyer, Jaenisch, & Young, 2007; Ng, Robert, Young, & Struhl, 2003). It remains to be investigated in future studies, whether *BRU1* is required for the maintenance of H3K4 methylation at memory genes or for the control of nucleosome occupancy at these loci. Due to the heterogeneity of whole seedlings and technical limitations, chromatin immunoprecipitation analyses provide a relatively coarse picture and are to be interpreted with caution. Our findings extend previous reports on the function of *BRU1* in the key point that *BRU1* may not only be required for the inheritance of repressive chromatin states, but also for the inheritance of active chromatin states that

are conducive to ongoing transcription. This suggests a mode of action where *BRU1* does not bind to individual chromatin modifications that are to be copied but may act more generally in the faithful inheritance of such chromatin modifications. This may be achieved by providing a binding platform for various reader and writer enzymes or by ensuring the transmission of the epigenetic information from “old” nucleosomes onto “new” nucleosomes.

We found that *CAF-1* is not required for HS memory. This is a noticeable difference to other phenotypic defects that have been observed in *bru1*, such as stem fasciation and DNA damage repair (Kaya et al., 2001; Takeda et al., 2004). It suggests that although *CAF-1* and *BRU1* act in connected pathways, their functions do not fully overlap. Notably, *CAF-1* has been implicated in the priming of plant defences, as it modulates nucleosome occupancy of primed genes (Mozgova et al., 2015). Whether *BRU1* is also required for defence priming or stress memory in response to other biotic or abiotic stress, cues remains to be investigated.

HS memory at the physiological level was reported to last for at least 3 days (Stief et al., 2014). At the molecular level, a memory after HS as evidenced by enhanced reinduction after a second HS has been detected for up to 7 days (Liu et al., 2018). The HS treatment that is used to activate the memory response (ACC or an even milder

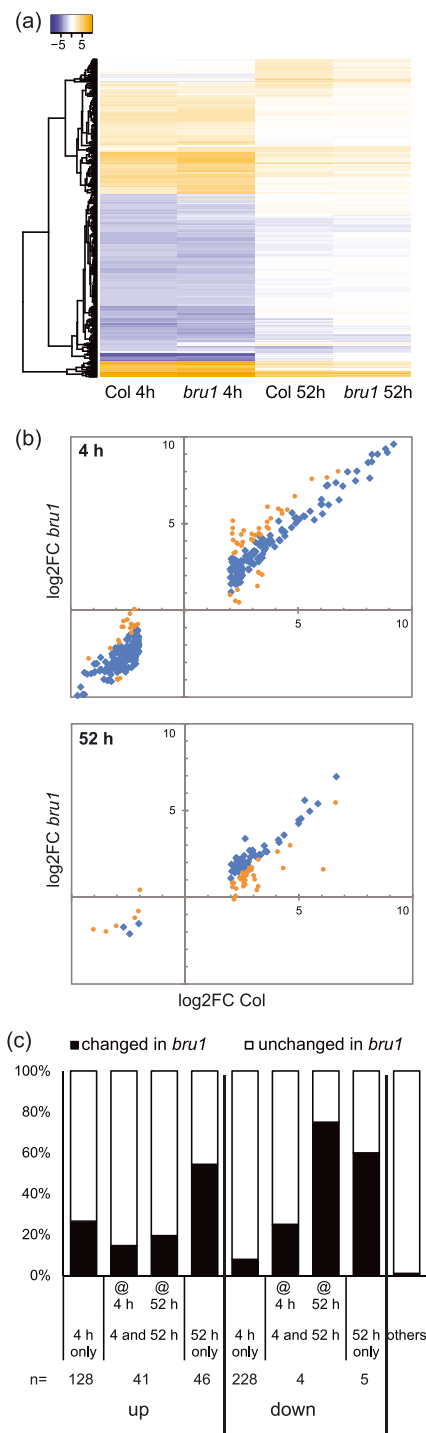


FIGURE 7 Global gene expression analysis after acclimatizing heat stress (ACC) in *bru1-2*. (a) Clustered heat map analysis including all 452 differentially expressed genes (DEGs) with log₂FC 2 or -2 in Col-0, including 356 “4 hr only” DEGs, 45 “4 and 52 hr” DEGs, and 51 “52 hr only” DEGs. Scale indicates log₂FC relative to the NHS control for Col-0 and *bru1-2*. (b) Expression correlation analysis of DEGs (log₂FC 2 or -2) at 4 h (top panel) and 52 h (bottom panel) in Col-0 and *bru1-2*. DEGs that differ in *bru1-2* at least two-fold from the value of Col-0 are highlighted in orange. (c) Percentage of DEGs whose induction or repression differed at least twofold in *bru1-2* compared with Col-0 in the indicated classes. The total number of DEGs in these classes is indicated with n. The number of differentially expressed genes is enriched among the heat stress-responsive genes compared with the rest of the genome (others)

treatment) does not cause visual damage and only a minimal delay in growth (Stief et al., 2014). Hence, considerable growth is taking place during the memory period that may at least partially be attributed to ongoing cell division. This is in line with our finding that ACC reduces histone H4 expression, as a marker gene for the S-phase, only transiently and moderately. Although detailed further investigations will be required to determine cell division rates in different tissues after ACC, it appears plausible that the memory is transmitted over at least a few cell divisions. This raises the question of how memory components are inherited during DNA replication and cell division. Previous work has demonstrated that histone modifications as well as nucleosome occupancy both regulate HS memory (Brzezinka et al., 2016; Lämke et al., 2016). It is tempting to speculate that *BRU1* may play a role in the inheritance of HS memory determinants through DNA replication and their faithful transmission to daughter cells.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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