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CONCEPTUAL REVIEW ARTICLE

The Many Shades of Bilingualism: Language Experiences Modulate Adaptations in Brain Structure

Christos Pliatsikas [a,b], Vincent DeLuca [c], and Toms Voits [a]

[a]University of Reading, [b]Universidad Nebrija, and [c]University of Birmingham

Recent years have seen an expansion in the research related to structural brain adaptations related to the acquisition and processing of additional languages. However, the accumulating evidence remains to a great extent inconsistent, with a large variety of cortical, subcortical, and cerebellar effects reported in various studies. Here we propose that the variability in the data can be explained by the differences in the language background and experiences of the tested samples. We also propose that the field should move away from monolithic bilingual versus monolingual comparisons; instead, it should focus on the experiences of the bilingual groups as predictors of structural changes in the brain, and also employ longitudinal designs to test the dynamic effects of active bilingualism. The implications of the proposed approaches for the suggested benefits of bilingualism on ageing and patient populations are also discussed.

Keywords bilingualism; brain structure; ageing; individual differences; neuroplasticity

Bilingualism and Neuroplasticity. Where Are We?

The past decade has seen a boom in evidence that learning and using additional languages causes structural adaptations in the brain. These adaptations have been expressed as volumetric and/or shape changes in cortical and subcortical

Correspondence concerning this article should be addressed to Christos Pliatsikas, School of Psychology and Clinical Language Sciences, University of Reading, Harry Pitt Building, Whiteknights, Reading, RG6 6AL, United Kingdom. Email: c.pliatsikas@reading.ac.uk

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regions underlying language learning and control, as well as adaptations in the diffusivity of white matter tracts connecting these regions (for a detailed review see Pliatsikas, 2019a). The available evidence has come from a variety of bilingual populations, including children, younger and older healthy adults, and patients, with distinct profiles of language backgrounds and use, including simultaneous and sequential bilinguals, individuals immersed in a bilingual environment, and simultaneous interpreters. However, and perhaps understandably, the evidence that has emerged from such a diverse collection of samples has appeared inconsistent, and therefore inconclusive with respect to how bilingualism affects brain structure, and seemingly inadequate to contribute to a theoretical framework describing these effects; indeed, while some groups only demonstrated cortical grey matter adaptations, others demonstrated only subcortical ones, and others only white matter adaptations. Several explanations have been put forward to address this variability, including the methodological inconsistencies between studies (e.g., different MRI scanners, different analytical methods, etc.; García-Pentón, Fernández García, Costello, Duñabeitia, & Carreiras, 2016), as well as concerns about the statistical power of some of these studies (Munson & Hernandez, 2019). However, a key factor may be the aforementioned diversity in the tested samples, and also the fact they have typically been simply compared to monolingual groups with no account of the quality and quantity of their bilingual experiences (Luk & Pliatsikas, 2015). This issue is not unique to this particular literature; indeed, similar practice in behavioral and functional neuroimaging literature have led to recent calls for the field to shift toward more elaborate designs that take into account the individual experiences of the bilinguals. For example, de Bruin (2019) argued that despite bilinguals and monolinguals typically being treated and compared as two uniform and distinct groups, it is very rare that two bilinguals are the same. Instead, a bilingual is defined by his/her experiences, including age of acquisition, immersion in a bilingual environment, quantity, and quality of switching between languages, and so on. Moreover, Surrain and Luk (2019) surveyed the literature and reported that bilinguals are most typically described by their L2 proficiency level but very rarely by usage-based measures or by the sociolinguistic context they found themselves in. These observations beg the question of whether the variability of the findings (structural or otherwise) will be more meaningful if viewed through an experience-based perspective, and whether the field should shift toward designs that take into account these experiences. The next sections of this article present a recent theoretical suggestion accounting for the effects of bilingual experiences on neuroplasticity, followed by examples of recent approaches accounting for these experiences. It

concludes with some discussion regarding the implications of these approaches for ageing and patient populations.

The Dynamic Restructuring Model

Based on the suggestions that individual differences in bilingual experiences might explain the reported variability in bilingualism-induced neuroplasticity, Pliatsikas (2019b) revisited the available literature and evaluated it according to the linguistic experiences of the tested samples. He put forward three interesting observations: First, that simultaneous bilinguals showed similar patterns of structural adaptations as immersed sequential bilinguals only (i.e., bilinguals with substantial experience in using their second language). These effects were mainly found in the shape and volume of the basal ganglia and the thalamus (Burgaleta, Sanjuán, Ventura-Campos, Sebastián-Gallés, & Ávila, 2016; Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2017), as well as the integrity of white matter structures such as the inferior fronto-occipital fasciculus (IFOF) and the corpus callosum (CC; García-Pentón, Pérez Fernández, Iturria-Medina, Gillon-Dowens, & Carreiras, 2014; Mohades et al., 2012). Second, that cortical grey matter effects were mainly reported in young adult sequential bilinguals with limited immersion in bilingual environments, but also in older lifelong bilinguals; conversely, subcortical and white matter adaptations were mainly reported in experienced bilinguals, young and old (Luk, Bialystok, Craik, & Grady, 2011; Pliatsikas, Moschopoulou, & Saddy, 2015). Third, adaptations in simultaneous interpreters, which arguably have the most frequent and intense language switching needs, were reported as *reductions* in grey matter volume and white matter integrity when compared to non-interpreter bilingual or multilingual controls. Particular trajectories of structural adaptations were also observed in language training studies, where cortical grey matter adaptations appeared to be followed by white matter and subcortical grey matter adaptations, while the original grey matter adaptations disappeared in more experienced users. Pliatsikas (2019b) suggested that structural adaptations in the brain are dynamic, can go through cycles of local tissue increases and decreases during language learning (with a cycle kickstarted every time a new language is acquired), and cannot be viewed independently of where in the cycle of additional language learning and use the bilingual is.

Based on these observations, Pliatsikas put forward the dynamic restructuring model (Pliatsikas, 2019b), a theoretical framework organizing the available evidence according to the bilinguals' place in the cycle of learning and using an additional language. Based on previous models explaining neuroplasticity during the acquisition of a new skill (Lövdén, Bäckman, Lindenberger, Schaefer, &

Schmiedek, 2010), Pliatsikas proposed that the reported bilingualism-induced effects can be classified into three distinct stages of language learning and use: At Stage 1, where participants are **initially exposed** to a second language, either by means of immersion in a foreign environment or in a language training course, increases in grey matter volume are reported in a series of brain regions related to vocabulary acquisition (for example, the inferior and superior parietal lobules, the anterior temporal lobe and Heschl's gyrus) and language control (for example, the inferior and middle frontal gyri and the anterior cingulate gyrus). Since language learning typically entails vocabulary learning, especially in classroom-type instruction, these findings indicate that the related brain regions respond to the increased demands for efficient vocabulary learning and controlling between lexical alternatives by increasing their size, possibly by creating more local neural connections. With increased exposure to a second language environment (i.e., with increased L2 experience) the initial growth of these regions disappears, possibly due to the process of pruning after efficient connections are identified. The L2 learners are now entering Stage 2, or the **consolidation** stage, where the weight shifts from vocabulary acquisition to grammatical and phonological acquisition (Caffarra, Molinaro, Davidson, & Carreiras, 2015; Flege, 2009; Pliatsikas & Marinis, 2013), and subsequently to control of lexical, phonological, and grammatical alternatives. It is in these bilinguals that subcortical and cerebellar adaptations first emerge, in regions that are central to language control (Abutalebi & Green, 2016). This is also when adaptations in white matter tracts such as the inferior and superior longitudinal fasciculi (ILF and SLF) and the IFOF first emerge, as the brain becomes more efficient in relaying information between frontal, temporal, and parietal regions involved in semantic, phonological, and syntactic processing. Similarly, this is the stage where adaptations are reported in the CC, a tract crucial to executive control (Just, Cherkassky, Keller, Kana, & Minshew, 2007). With increasing experience bilinguals are expected to reach Stage 3, that of **peak efficiency**, with simultaneous interpreters being the best representatives of this stage. This is when adaptations reported at Stage 2, mainly white matter and subcortical grey matter changes, are expected to slowly disappear, possibly signifying pruning processes, at least in grey matter, resembling the reversing at Stage 2 of the effects from Stage 1. In white matter, the previously reported frontal adaptations are replaced by more posterior adaptations of the same tracts. This possibly signifies increased automatization/efficiency, which requires less involvement of frontal regions (see also Grundy, Anderson, & Bialystok, 2017). Although the last stage is the less well-described, due to the relative scarcity of evidence, the dynamic restructuring model proposes that brain modulations

are dynamic and continuous and can be predicted by the bilingual experiences. This suggests that the typically employed between-groups bilingual versus monolingual comparisons might be inadequate to capture the full extent of the effects of bilingualism on the brain, and certainly inappropriate to investigate the dynamicity of these effects.

It is important to point out that the dynamic restructuring model is not a model about second language acquisition (lexical, grammatical, or otherwise) or processing, or even control; it is a model about the neurostructural correlates of the above processes, and, crucially, their trajectories. As such, it is compatible with related models of bilingualism-induced neuroplasticity, such as the adaptive control hypothesis (ACH; Abutalebi & Green, 2016) and the bilingual anterior to posterior and subcortical shift (BAPSS) model (Grundy et al., 2017), which also link structure to function. The dynamic restructuring model complements the ACH by accounting for newer findings, especially with respect to white matter plasticity, and by adding a temporal dimension and dynamicity to its predictions; it also accounts for the reductions reported in highly experienced language switchers, like simultaneous interpreters, which are not accounted for by the BAPSS. Finally, it accounts for the limited findings from multilinguals, in an attempt to place all types of bi-/multilingual experiences on a continuum (see also Pliatsikas, 2019b).

Moving Forward: Examining the (Long-term) Effects of Individual Experiences on Brain Structure

The need for the field to move away from dichotomous bilingual/monolingual comparisons has recently been acknowledged by a few studies employing a variety of new approaches that put individual experiences/differences of bilinguals at center stage. Such approaches are in accordance with the basic premise of the dynamic restructuring model and will help further elaborate the effects of bilingualism on the brain, and ultimately the model itself. The remainder of this section describes the two general approaches that have recently been used in this direction.

One approach is the use of cross-sectional designs, which examine individual differences in bilingual language use, using multiple factors to examine their respective effects. Ideally, factors related to type, profile, duration, and intensity of bilingual language use are examined, as these will likely interact with respect to delimiting the latency and extent of neuroanatomical adaptation. A handful of studies have examined such effects within bilingual groups, usually in the absence of a monolingual control group. Results from these studies provide support for aspects of the dynamic restructuring model,

specifically adaptations at specific stages of bilingual language exposure and use. For example, Nichols and Joannise (2016) examined neurocognitive effects of L2 age of acquisition (AoA) and proficiency. They reported a positive correlation of AoA and white matter integrity in several tracts including the CC, arcuate fasciculus (AF), and ILF. Some overlapping effects were found by DeLuca, Rothman, Bialystok, and Pliatsikas (2019) who reported a positive correlation with AoA and white matter integrity in the CC. This study also reported longer duration of L2 exposure to correlate with reshaping in subcortical structures associated with language control, including the caudate nucleus and thalamus. Another recent study by Hervais-Adelman, Egorova, and Golestani (2018) tested multilinguals and reported positive correlations of both volumetric and shape adaptations in the caudate nucleus with the degree of multilingualism, as determined by a composite measure relating to length of use and proficiency. Taken together, these studies indicate that prolonged L2 learning and/or use leads to increased efficiency, which is expressed by continuous and dynamic restructuring of brain regions involved in language control. A more recent approach that follows similar principles has been put forward by Gullifer and Titone (2019), who presented a measure of language *entropy* as a predictor of neurofunctional modulations in the bilingual brain. Language entropy is a single measure accounting for the individuals' history in all of the spoken languages (and partially capturing the profiles of language use distinguished in the ACH) and provides additional predictive power over more traditional predictors such as amount of immersion or age of acquisition. Although this approach has not been tested on structural brain data yet, language entropy has been shown to modulate resting state functional connectivity in the bilingual brain (Gullifer et al., 2018), suggesting that this is a promising future avenue for the study of brain structure too.

The second approach that is clearly relevant to the predictions of the dynamic restructuring model, and to the field in general, is the use of longitudinal designs with bilinguals. These designs provide ideal within-subjects measures of language use, and their interactions with brain structure. The majority of longitudinal studies to date cover mainly language acquisition and early aspects of exposure in highly instructed training environments. These studies suggest that the brain responds to initial learning via increases in cortical grey matter volume in regions associated with language processing and control. For example, Mårtensson and colleagues (2012) reported volumetric increases in several regions associated with language acquisition and processing, specifically the inferior, middle, and superior frontal gyri (IFG, MFG, and SFG) and the hippocampus. Stein et al. (2012) echoed some of these findings by reporting

increased grey matter volume in left IFG and anterior temporal lobe (ATL) in L2 learners of German living in Switzerland. Support for a notion of *consolidation* in neuroanatomical adaptation to L2 use has also been seen in longer term exposure. Hosoda, Tanaka, Nariai, Honda, and Hanakawa (2013), for example, found increases in structural connectivity between cortical and subcortical regions (specifically IFG and caudate nucleus) in Japanese L2 learners of English who were consistently practicing for a year. To date, and to the best of our knowledge, only one study has examined later stages of bilingual language use in adults with a longitudinal design that did not involve language training. DeLuca et al. (2019) tested longer-term neuroanatomical effects of language use in already immersed bilinguals. They reported volumetric increases in the cerebellum, which were positively correlated with the amount of prior immersion, accompanied by subcortical restructuring and increases in diffusivity in the forceps minor (an anterior extension of the corpus callosum connecting it to the frontal lobes). These findings were interpreted as increased automation and efficiency of bilingual language processing with prolonged intensive L2 exposure, suggesting that the effects of bilingualism on brain structure are dynamic in nature and can be observed even in highly experienced bilingual users.

The Dynamic Effects of Bilingualism and Their Implications for Later Life

Since the effects of active language use on brain structure are observable in bilinguals across different ages and independently of language training, it is important to look at how this "enhancement" of brain structure might interact with brain decline as brought about by healthy ageing or neurodegenerative diseases. While the body of research looking at bilingualism in ageing and patient populations is comparatively smaller, initial evidence shows that adaptations in brain structure do indeed extend to the older age. These studies report monolingual and bilingual group differences, in a way where healthy older bilingual population exhibit resilience to age-related neurodegeneration. This resilience is expressed as preservation of grey matter in brain areas implicated in language acquisition and control, such as the dorsolateral prefrontal cortex, anterior cingulate cortex and ATL (Abutalebi et al., 2014, 2015), the IFG and IPL (Borsa et al., 2018; Heim et al., 2019), and the hippocampus (Voits, Robson, Rothman, & Pliatsikas, 2019), and higher integrity in white matter tracts such as CC, ILF, and IFOF (Anderson et al., 2018; Gold, Johnson, & Powell, 2013; Luk et al., 2011), all regions central to the predictions of the dynamic restructuring model, especially at Stages 2 and 3. All of this adds to the idea of bilingualism as a contributing factor to a *neural reserve* (i.e., build-up of *structural scaffolding* of

neural tissue in the brain, supporting it against tissue or synaptic loss). It is worth noting that these studies typically tested lifelong bilinguals (i.e., individuals with extensive experience in switching between languages) who have presumably gone through all the stages described by the dynamic restructuring model, implying long-term neuroplastic effects.

The suggestion of a bilingualism-induced neural reserve has raised the question of whether bilingualism has clinical implications in the form of protection from healthy and/or pathological neurodegeneration, which might even extend to delay of the clinical symptoms of neurodegenerative diseases such as Alzheimer's (Perani & Abutalebi, 2015). The related literature is relatively recent, and it initially involved examining clinical records of life-long bilinguals, which showed that bilingualism may delay the onset of clinical symptoms of dementia by 4 to 5 years (Alladi et al., 2013; Bialystok, Craik, & Freedman, 2007). The direct evidence from brain structure is quite limited, but the effects of neural reserve have been observed in clinical Alzheimer's disease (AD) and mild cognitive impairment (MCI) populations: Duncan and colleagues (2018) reported French-English bilingual patients to have higher cortical thickness in language and cognitive control areas than monolinguals. A more common finding in clinical populations is that bilingual clinical populations have a greater extent of brain atrophy than cognitively matched monolingual populations (Gold, Kim, Johnson, Kryscio, & Smith, 2013; Schweizer, Ware, Fischer, Craik, & Bialystok, 2012), suggesting a bilingualism-induced increase in neural connectivity and more efficient use of spared neural tissue, or a *cognitive reserve*. This finding is further supported by other proxy measures, such as reduced resting state brain metabolism, which indicates lower synaptic activity in bilinguals, while maintaining cognitive performance corresponding with a higher rate of metabolism in monolingual AD patients (Perani et al., 2017).

If bilingualism is shown to counteract cognitive and/or brain decline related to AD and MCI, it might be the case that its beneficial effects are not constrained to these diseases only, although other neurodegenerative disorders have hardly been studied in this context (Voits, Pliatsikas, Robson, & Rothman, 2019). For example, there are very few studies examining progressive neurodegeneration in diseases such as Huntington's and Parkinson's in connection with bilingualism. Studying these conditions in bilinguals may prove highly informative, as they primarily target the basal ganglia, a group of structures that are commonly reported to be affected by bilingualism, especially in more experienced bilinguals, as per the dynamic restructuring model suggestions. However, a recent study reported bilingualism to only be associated with increased grey matter volume in inferior frontal gyrus and significantly increased metabolism in an

array of cortical regions in Catalan-Spanish bilingual Huntington's disease patients, without reporting any subcortical effects (Martínez-Horta et al., 2019). Bilingualism and Parkinson's disease have not been yet studied at the brain level, but it has been shown that increased cognitive reserve in general (as measured by an overall cognitive lifestyle score) results in better cognitive and motor outcomes in Welsh-English bilinguals (Hindle et al., 2017). Similarly, preliminary results have been presented pointing toward a cognitive reserve in bilinguals diagnosed with multiple sclerosis, a disease that primarily affects the white matter (Aveledo et al., in press). It even seems to be the case that bilingualism-induced neural efficiency may prove beneficial in cases of acute neural tissue loss. Significantly more bilinguals than monolinguals report intact cognitive functions following a stroke (Alladi et al., 2016) and bilingual individuals experience less severe post-stroke aphasia (Paplikar et al., 2019). These results have been interpreted as evidence for faster, more efficient, rewiring of lost connections and adapting to a new situation following sudden onset brain damage. In sum, although the limited available evidence points to benefits of bilingualism in the case of neurodegenerative diseases beyond AD, much more work needs to be done to understand the tangible clinical repercussions of bilingualism. However, the common denominator of the available evidence is that it has been observed in patient groups from bilingual regions (India, Quebec, Catalonia, and Wales), suggesting a link between these benefits and active use of two languages.

Putting It to the Test

Since the dynamic restructuring model was conceived mostly based on previously published data, its specific predictions should, and could, be directly tested with tailored designs. For example, a long-term longitudinal design conducted in highly proficient bilinguals that are freshly immersed in a L2-speaking environment should see them cycling through the three stages as an effect of immersion, starting from cortical grey matter restructuring at the start of immersion, gradually decreasing before giving way to subcortical and cerebellar restructuring and white matter enhancement. Similar effects would be expected in tri-, quatri-, n-linguals immersed in an Ln environment, although it is possible that a previously optimized language control mechanism would face smaller scale adaptations. It is also possible that the adaptations within the stages themselves might vary between different groups of bilinguals for example, and reconciling with the predictions of the ACH. Bilinguals in dense code-switching contexts, where the demands for switching and control are the highest, may transition faster between the three stages, especially between Stage

2 and 3, than bilinguals in dual-language contexts, who in turn might transition faster than those in single language contexts.[1] It is also possible that, since these effects are dynamic, switching between contexts might interrupt this trajectory, or even backtrack it. In the context of the BAPSS model, this would mean an interruption of the shift to posterior structures, with less reliance on them observed in bilinguals that face smaller language switching demands. Turning to ageing bilinguals, it might be the case that the proposed neural reserve will be contingent upon the stage the bilinguals find themselves into, in that while lifelong bilinguals will experience benefits across the board, bilinguals with limited immersion might only report benefits in brain structures affected at Stage 1. Similar predictions could be made for patient studies, in that benefits for the brain are more likely to emerge in highly experienced bilinguals.

Concluding Remarks

This article has used contemporary theories and evidence to show that the location, type, and trajectory of neuroplasticity related to bilingualism is inextricably linked to nuances related to the individual experiences of the bilinguals, which cannot be reliably and consistently captured by traditional bilingual versus monolingual comparisons. We therefore endorse the view that the field should shift toward longitudinal designs that describe the trajectory of these effects by taking into account the quantity and quality of bilingual language use, an approach that also applies to the study of bilingualism-induced adaptations in cognition and brain function. Given the implications that active bilingualism might have for later life, an emphasis should be placed on examining the brain and bilingualism across various clinical disorders, both cross-sectionally and also longitudinally, to study effects of bilingualism on the rate of brain decline over time and any structural differences arising as a result of language use patterns. In all cases, we maintain that it is paramount to move beyond the simplistic binary view of bilingualism as a categorical variable, treat bilingualism as the nuanced experience it is, and identify factors that contribute to anatomical changes in the brain across the whole lifespan.

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Note

1 It is worth noting here that the ACH and its derivatives (Green, 2018) have also described an "open control" context, which might imply a specific rather than global interference from L2 (e.g., interference at the level of selecting equally active language alternatives during production, which in turn implies reactive suppression of the non-selected item).

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Appendix: Accessible Summary (also publicly available at https://oasis-database.org)

Pliatsikas, C., Deluca, V., & Voits, T. (2019). The manifold effects of bilingualism on brain structure, and their implications for ageing and neurodegeneration. Article accepted in *Language Learning* on August 8, 2019.

The Manifold Effects of Bilingualism on Brain Structure

What This Research Was About and Why It Is Important

Recent evidence has shown that the experience of learning and using additional languages can cause measurable changes in the brain regions involved in language acquisition and control; however, this evidence remains fragmented. In this article, the authors revisited the available findings and presented a recent experience-based model of brain plasticity which attempts to unify them. The authors proposed future research avenues and explored how these proposals relate to suggestions for protective effects of bilingualism in older age.

What the Researchers Did

- We point out clear distinctions regarding the parts of the brain that might be affected by bilingual experience. Long-term, experienced bilinguals show adaptations in regions mainly related to language control. Adaptations in bilingual individuals who are still acquiring, and/or have limited experience in using, their second language, are mostly found in regions related to vocabulary acquisition.
- We summarize the dynamic restructuring model (DRM; Pliatsikas, 2019b), which proposes that adaptations occur in distinct stages across time, as the brain becomes efficient at handling multiple languages.

What the Researchers Found

- Most of the available literature compares bilinguals and monolinguals; however, the predictions of the DRM would be better tested within bilinguals. Therefore, two future directions are proposed:
- First, we need measures of individual differences in bilingual language use to investigate how different experiences lead to different adaptations. The limited evidence available shows that longer exposure to additional languages is marked by dynamic adaptations that signify more efficient language control;
- Second, longitudinal studies are encouraged, that focus on bilingualism-induced adaptations over long periods of time. Most evidence comes from language training studies and shows initial adaptations in regions related to language acquisition. However, one longitudinal study on experienced bilinguals suggests that with prolonged experience these adaptations give way to others, in regions linked to language control.
- Finally, we highlight the implications of these findings and the predictions of the DRM for later life, in light of recent suggestions that bilingualism can interact with brain decline in healthy ageing or in patients with neurodegenerative diseases. Compared to monolinguals, healthily ageing bilinguals tend to show better preservation of regions related to language acquisition and control, similar to the regions highlighted by the DRM. The limited research on progressive and acute neurodegenerative diseases (e.g., Alzheimer's and stroke, respectively) has shown better preservation of cognitive functions in bilingual patients, suggesting more efficient recruitment of the spared brain tissue. This finding appears related to active long-term bilingualism, but given the limited evidence, this suggestion remains tentative.

Things to Consider

- The field is still relatively young but promising; importantly, the seemingly contradictory findings to date actually appear to fit into a trajectory of adaptation, if viewed from an experience-based perspective.
- Bilingualism should not be viewed as a monolithic attribute, but as a nuanced and dynamic experience.
- Bilingualism could be studied as a cost-effective strategy against ageing- and disease-related brain decline.

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