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The crucial role of working memory in intellectual functioning.

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Abstract

Cognitive psychology offers an important contribution to the understanding of the mechanisms underlying intelligence. In this paper, we synthesize the research showing that, among the different cognitive mechanisms associated with intelligence, working memory has a particularly high explanatory power, especially when considered in its active component involving not only the maintenance (as in short-term memory) but also the manipulation of information. The paper considers two main implications of this finding for the applied and clinical fields. For a start, we examined how intelligence tests take into consideration working memory. Secondly, we considered the highly debated literature on the effects of working memory training on intellectual performance. Theoretical and applied implications for the relationship between WM and intelligence are discussed.

Keywords: working memory, intelligence, attentional control, short-term memory, speed of processing, executive functions.

Introduction

In general, intelligence can be defined as “a very general mental capability that, among other things, involves the ability to reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience” (Gottfredson, 1997, p. 13). Broad definitions of intelligence typically do not offer a psychological description of the mental operations and functions underlying this construct. However, recent cognitive research on the psychological bases of intelligence has produced a series of proposals associating intelligence to simple cognitive mechanisms. This is based on the assumption that inter-individual variations in one or more simple mechanisms might explain substantial portions of the variance observed in either measures collected through traditional assessments of intelligence or comparisons between groups assumed to have different intellectual abilities. In this paper, we examine how research into basic mechanisms, in particular working memory (WM), might help our understanding of the nature of intelligence. Due to the conceptualizations ways of assessing intelligence, this paper considers the broad definition of intelligence, with reference to the psychological construct typically measured by IQ tests.

Assumptions about the mechanisms underlying intelligence are relatively new in the history of psychology. These studies are usually held to have started with Galton’s effort (1869) to measure intelligence by processing speed tests. However, for a long time, research on intelligence was carried out on a psychometric basis. In recent years, to the contrary, there has been a growing interest not only in intelligence but also in its cognitive characteristics. For example, a literature search using Psych Info¹ found 16,434 papers published from 2001 to 2011 that included the term “intelligence” or related terms and 392 that specifically included “intelligence” in association with “working memory”.

The growing interest of basic research into the construct of intelligence arises from various areas, particularly from cognitive psychology, which studies the cognitive mechanisms underlying intelligence (see the special issue edited by Cornoldi, 2006), cognitive neurosciences, which are

interested in the neural correlates of intelligence (see Deary, Penke, & Johnson, 2010), and clinical psychology, which is focused on understanding intellectual failures and developing appropriate assessment and intervention procedures in clinical samples (see Wilhelm & Engle, 2005).

Cognitive Mechanisms Underlying Intelligence: Speed of Processing, Executive Functions, and Working Memory

Recent developments in research on intelligence have focused on a series of cognitive mechanisms that could represent the core of intellectual functioning. In this section, we shortly examine three mechanisms that have received particular consideration: Processing Speed (PS), Executive Functions (EF), and WM. We will try to distinguish them, by focusing on research that has specifically examined the implications of one of them, but we will also comment the fact that they partially overlap.

The association of PS to intelligence has been raised by many studies, starting from the early work of Galton (1869), as it has been hypothesized that rapid basic mental operations support complex cognitive processes (see Jensen, 2006, for a review). In fact, high speed of processing may guarantee that important information held in memory is not lost and the necessary associations are rapidly established in the mind, thus supporting reasoning and comprehension processes. In fact, measures of processing speed measures, despite their issues with reliability (Bittner, Carter, Kennedy, Harbeson, & Krause, 1986), provide important information on intellectual functioning. Evidence strongly supports that even simple fast inspection tasks correlate with measures of intelligence (with a mean value of .50 according to the meta-analysis of Grudnik and Kranzler, 2001). Although, it has also been observed that the correlation between processing speed measures and intelligence is moderate but never especially high (Hunt, 1980, 2011) also taking into account the fact that the correlations between IQ

and PS measures are overestimated by the fact that IQ tests also include speed measures (see Wilhelm & Schulze, 2002) (like the Wechsler scales) or time limitations (like many group administrable tests).

The PS hypothesis poses a series of problems. For example, solving many complex intellectual problems often requires spending more time on the tasks, rather than responding quickly. Highly creative, gifted individuals may reach exceptional goals without having a particularly high PS (Reams, Chamrad, & Robinson, 1990). Another crucial question is whether speed measures actually describe an individual's response time for a single trial or other cognitive mechanisms, such as attentional control or WM. In fact, many PS measures are collected by proposing a series of trials and measuring how many trials were carried out in a certain time period or by calculating the mean response time on the basis of a series of observations. Thus, PS measures could primarily describe attentional control ability, which is an individual's ability to maintain a sustained rhythm for a period of time, rather than the subject's optimal speed. Along these lines, it has been observed that the subject's best performances (representing the highest speed possible for the subject) typically do not offer an adequate description of that particular individual's abilities (Coyle, 2003). Furthermore, WM may have a role in PS measures, because processing speed tasks also require keeping in mind the task requests and other specific information. On this respect, it has been shown that increases in the relationship between PS and intelligence may correspond with increases in the quantity of information that has to be maintained in WM during the response speed tasks (Wilhelm & Oberauer, 2006). In fact, studies trying to differentiate the specific contributions of PS, and other cognitive mechanisms like WM or also secondary memory, suggest that all the mechanisms may explain a specific portion of variance, but WM is the most powerful predictor (Redick, Unsworth, Kelly, & Engle, 2012; Unsworth, Brewer, & Spillers, 2009).

Executive functions (EF) have been also frequently associated with intelligence. While definitions of EFs vary, the basic definition originating from neuropsychology, holds that they are the

set of operations associated with frontal cortex functioning, such as updating information in WM, inhibition, shifting (Miyake et al., 2000), planning, organizing, categorizing, using abstract rules, and tolerating the delay of gratification (Duncan, Burgess, & Emslie, 1995). This set of operations is typically involved in reasoning and other complex cognitive activities characterising intellectual functioning. The association between EFs and intelligence has been strongly supported, in particular by the neuropsychological literature, on the basis of the observations that frontal cortex size is critically involved in intellectual functioning, as it is more developed in intellectually mature individuals and lesions in frontal cortex may impair intellectual functioning (see Duncan, 2005). Furthermore, the association is supported by different sources of information (see Kane & Engle, 2000; Kochanska, Murray, Jacques, Koenig, & Vandegees, 1996; Miyake, et. al., 2000) beyond neuroscience. For example, it has been shown that EFs are good predictors of intelligence in children (Brydges, Reid, Fox, & Anderson, 2012) and that intellectually impaired individuals have poor EFs (Hartman, Houwen, Scherder, Visscher, 2010).

However, EFs , as an explanation for intelligence, present difficulties. The psychological definition of EFs is vague and includes various heterogeneous functions (Chan, Shum, Touloupoulou, & Chen, 2008). For example, it is difficult to consider delayed memory or task shifting as signifiers of an unique psychological mechanism. Similarly, hot and cool executive functions seem differ on many respect and have different implications for intellectual functioning (Hongwanishkul, Happaney, Lee, & Zelazo, 2005). As well, some EFs seem to be preserved in the presence of severe frontal lesions (Roca et al., 2010). Moreover, some prefrontal functions are not highly related with intelligence, while other brain areas seem more critically related with specific, important intellectual functions (Todd & Marois, 2004).

Due to the fact that the concept of EF includes many different functions, including attentional control during processing speed tasks and Working Memory, if the EF hypothesis is to be maintained,

then an in-depth study to ascertain which functions are most related with intelligence is needed. On the basis of the available evidence, these functions seem to be related with controlled WM (see Engle, 2010), and the ability to update information in WM (Friedman, Miyake, Corley, Young, Defries, & Hewitt, 2006). This evidence supports the centrality of WM in intellectual functioning.

The consideration that intellectual operations are carried out based on temporarily maintained information and are guided by goals and mental sets, which are also temporarily maintained, provides a theoretical basis for the hypothesis that WM supports intelligence (Case, 1985). Pioneering studies in cognitive psychology (Just & Carpenter, 1992) have suggested that intellectual performance may be enhanced if the individual is able to maintain more information in a temporary store and to simultaneously process it, initiating a long series of studies that have rapidly expanded in the past decade.

Part of the evidence about the relationship between intelligence and WM is based on correlations. An early study by Kyllonen and Christal (1990) using relatively small samples presented impressively high correlations between WM and intelligence ($.80 < r < .90$), legitimating the hypothesis that WM and intelligence are highly related (Engle, 2002) but also giving rise to the risk of an overlapping between intelligence and WM measures and to the seemingly paradoxical suggestion that intelligence could be better measured by simply using WM tests. In contrast, Ackerman, Beier, and Boyle (2005) published a less enthusiastic meta-analysis, based on the use of a heterogeneous group of more than 60 different WM tests, which concluded that the correlation between WM and intelligence is moderate ($r=.48$). However, this moderate value could be due to the fact that the correlations analysed by Ackerman et al. (2005) focused on specific tests, rather than underlying factors. In fact, the correlation between WM and intelligence measured at the level of latent variables is typically higher (e.g., $r= .72$, Kane, Hambrick, Conway, 2005; $r=.85$, Oberauer, Schulze, Wilhelm, & Süß, 2005).

Many sources also confirm the predictive power of WM. For a start, from a developmental perspective, WM has a predictive power for intellectual performance also when age is partialled out (Belacchi, Carretti, & Cornoldi, 2010). Secondly, WM, above and beyond IQ, is the best predictor of literacy and numeracy (Alloway & Alloway, 2010), school readiness (Fitzpatrick & Pagani, 2012), and mathematical skills (Alloway & Passolunghi, 2011). Thirdly, it has been shown that some modern child prodigies have a moderate level of intelligence but extremely high performance in WM (Ruthsatz & Urbach, 2012). Fourthly, WM predicts success in complex tasks such as Texas Hold'em (Meinz, Hambrick, Hawkins, Gillings, Meyer, & Schneider, 2011) or piano sight-reading skills (Meinz & Hambrick, 2011).

In sum, the most recent evidence offers support to the view that WM is a crucial mechanism for understanding intellectual functioning. However, a complete understanding of the relationship between intelligence and WM requires a consideration of the models describing the specific organization of WM, in order to find which model best describes the relationship between WM and intelligence.

Models of Working Memory and Short-Term Memory

A model which has been used for examining the relationship derives from the original work of Baddeley and Hitch (1974) who first proposed the concept of WM in order to emphasize the ability not only to temporarily maintain information (the storage function, as specified by the concept of short-term memory [STM]) but also to work on the maintained information (the processing function). The classical model presented by Baddeley and Hitch proposed a tripartite organization of WM, distinguishing between a content independent component, involved in controlled processing of information (the Central Executive), and two content dependent components, respectively involved in maintaining verbal (the articulatory loop) and visuospatial information (the visuospatial sketchpad). Since then, many models of WM have been proposed, some of which include both the storage and

processing functions within the construct of WM (see Baddeley, 2000). Other models of WM are mainly focused on the processing function (Engle, Tuholski, Laughlin, & Conway, 1999) and specify its characteristics, by linking WM to attentional focus, inhibition of irrelevant information, and retrieval from secondary memory (Unsworth & Engle, 2007).

The possibility that WM and STM might reflect different functions and be differently related to intelligence is still debated (Alloway, Gathercole, & Pickering, 2006; Colom, Rebollo, Abad, & Shih, 2006). On one hand, it has been suggested that short term memory is the best predictor of the relationship between WM and intelligence (see Colom et al., 2006). This view has found support from the consideration that simple span tasks with long lists tap the same controlled mechanism as complex span tasks (Unsworth & Engle, 2006). It must be noticed that this result is particularly evident when active controlled operations, required to maintain supra-span material, and WM scores, with long list considering also partially recalled lists, are taken into account. It is also possible that the relationship is more evident with a particular modality, as simple span tasks with spatial stimuli may reveal stronger correlations with measures of intelligence than verbal spans (Kane et al., 2004). On the other hand, many models not only state that short-term memory and controlled WM must be distinguished, but also that the distinction is crucial for understanding the relationship between WM and intelligence. In fact, the distinction is present not only in the Baddeley model, but also in other models. For example, it has been hypothesized that WM tasks may be categorized as passive or active (Cornoldi & Vecchi, 2003) according to whether they only require a complete recall of the material as it was presented or the complex active manipulation of the maintained material. Some evidence suggests that the relationship between WM and intelligence primarily concerns the active rather than passive component of WM. For example, the variances in intelligence tests explained by complex (active) span tasks and by STM are partially different, and STM measures account for only a small part of the variances (Conway, Getz, Macnamara, & Engel de Abreu, 2011).

Evidence supporting the relationship between active WM and intelligence also comes from groups assumed to have different intellectual and cognitive abilities. For example, we (Cornoldi & Vecchi, 2003) examined the explanatory power of active WM in explaining why some groups have lower intellectual functioning (intellectually disabled children) and why other groups (e.g., learning disabled children), even though they have poor specific cognitive functioning, do not perform poorly in general intellectual functioning (see also Cornoldi, 2007, 2010). A comparative analysis of these groups showed a double dissociation. In particular, the case of people with genetic syndromes that produce general intellectual disabilities offers important information that is not biased by the fact that an intellectual disability could be diagnosed by using an intelligence test also involving WM. Studies on Down syndrome (Lanfranchi, Cornoldi, & Vianello, 2004) and Fragile-X individuals (Lanfranchi, Cornoldi, Drigo, & Vianello, 2009) show that their core deficit is in active WM, while in STM tasks, their performance may even exceed that of controls. On the contrary, evidence on children with dyslexia (Swanson & Siegel, 2001) or other specific learning disabilities (Palladino & Cornoldi, 2004) shows that individuals who have specific cognitive disorders but good general abilities may be impaired in STM but not in active WM.

In a study with a large group of young children, Giofrè and co-authors compared different WM models for their capacity of describing the relationship between WM and intelligence (Giofrè, Mammarella, & Cornoldi, submitted). Giofrè and co-authors found that a causal model considering a short-term memory latent factor, also including the storage component involved in active tasks, explained a relevant part of the variance in intelligence tests, but that active WM explains intelligence above and beyond STM.

Implications for the Assessment of Intelligence and the case of the WISC-IV

The hypothesis that WM is crucial for intellectual functioning has two important implications for the assessment of intelligence. For a start, it requires that traditional intelligence tests should be reconsidered in order to examine to what extent they also involved, although implicitly, WM. Secondly, it implies that modern measures of intelligence should also offer a direct estimation of WM.

In fact WM (as it also was the case of EFs, processing speed and other crucial cognitive mechanisms) has been typically involved in intellectual assessment, as in the case of the classical Binet tests and Wechsler scales (Roid, 2003; Wechsler, 2008), which included tasks involving WM as in the case of forwards and backwards digit spans and memory for sentences. Furthermore, as Just and Carpenter (1992) argued in a pioneering study, the classical Raven test, which places heavy weight on the *g*-factor as a core aspect of intelligence, strongly relies on the capacity of maintain different information in a temporary system and to simultaneously process it (see also Unsworth & Engle, 2005). In the new versions of the Wechsler scales (the Wechsler Intelligence Scale for Children, WISC-IV, and the Wechsler Adult Intelligence Scale, WAIS-IV), the reference to WM has become explicit. Here, we focus on the WISC-IV (Wechsler, 2004), not only globally the most widely used test for assessing children's intelligence, but also the most used psychological test in Europe (Evers et al., 2012).

Two main changes characterize the differences between the WISC-III and WISC-IV scales, and both are related to the increasing role attributed to WM. The first change is the reduction of the importance of the Full Scale Intelligence Quotient in favour of other indexes and the rejection of the traditional Verbal–Performance dichotomy in favour of four main indexes designed to represent the four main components of intelligence. The second change is the inclusion in the four indexes of a WM index, which replaces the Freedom from Distractibility Index, and is calculated with the classical Digit Span subtest (which includes the highly passive forward digit span and the relatively active backward

digit span), the new Letters-Numbers Sequencing subtest, and the reorganized and reinterpreted Arithmetic additional subtest.

In sum, the assumption of four distinct factors and indexes for the WISC-IV seems to give importance to WM. Moreover, the WM index is independent from other indexes, particularly the two main intelligence indexes (the Verbal Comprehension and Perceptual Reasoning indexes). Combined, these two latter indexes compose the General Ability Index (GAI), proposed by Prifitera, Saklofske, and Weiss (1998) for the WISC-III and then extended to the WISC-IV by Weiss, Saklofske, Prifitera, and Holdnack (2006). The GAI describes general cognitive functioning, including some subtests with a high loading on *g* factor and excluding the specific contribution of PS and WM. Therefore, the GAI can be used to study the relationship of this crucial WISC-IV index with independent WM measures. In addition, the WISC-IV measures of WM, as they can be distinguished, may help yield an accurate description of the relationship between different aspects of WM and general intellectual ability. For this reason, we analysed data collected on 2,200 children during the Italian standardization of the WISC-IV and found a high relationship between an intelligence factor and a WM factor ($r = .89$; Cornoldi, Orsini, Cianci, Giofrè, & Pezzuti, 2013). Furthermore, we computed the partial correlations between GAI and the weighted scores in each of the four WM measures collected with the WISC-IV administration (forward digit span, backward digit span, arithmetic and letters-numbers sequences), partialling out the contribution of the three non-interested subtests in the whole group of children, and we found that a ‘passive’ measure of STM, like the forward span, separated from the backward span, was poorly related to the GAI. In contrast, a highly active WM measure (the numbers-letters sequences task) had a relationship with GAI, above and beyond the specific contributions of the other WM measures, that was four times greater than the relationship between forward span and intelligence. More generally, the relationship increased in correspondence with increases in the degree of active control required by the WM tasks, as predicted by the assumption that all the WM tasks require some form of controlled

activity but the degree of required activity varies along a continuum going from the most passive tasks to the most active ones (Cornoldi & Vecchi, 2003; see also Carretti, Belacchi, & Cornoldi, 2010; Lanfranchi et al., 2004). It must be noticed that Belacchi et al. (2010) found a similar continuous relationship, administering a series of WM tasks varying in the degree of required active control and the Raven's Coloured Progressive Matrices (Raven, Raven, & Court, 1998). These observations confirm that new intelligence tests take into account the role of WM and may offer data in favour of a strong relationship between active WM and intelligence.

Implications for Projects Devoted to Improving Intellectual Abilities

If WM is crucial for intellectual functioning, then another implication is that the possibility of enhancing WM performance should be seriously considered (Gathercole, Dunning, & Holmes, 2012) and successful efforts to improve WM should produce similar effects in WM-related competencies, including intelligence (Barnett & Ceci, 2002; Shipstead, Redick, & Engle, 2010). However, this hypothesis has raised doubts based on the assumptions that intelligence and its underlying mechanisms are genetically predetermined and that experience cannot substantially modify them (Jensen, 1998); accordingly, the findings on the effects of WM training have been viewed with suspicion.

In our view, the issue should be considered from two angles: empirical data and its theoretical implications. In fact, there is considerable empirical evidence that WM training can improve performance not only in WM-related tests (Beck, Hanson, Puffenberger, Benninger, & Benniger, 2010; Klingberg et al., 2002, 2005; Mezzacappa & Buckner, 2010) but also in intelligence tests and, in particular, in tests with high load on g-factor among both the young, with effect sizes (Cohen's *d*) typically ranging between .65 and .98 (Jaeggi, Buschkuhl, Jonidas, & Perrig, 2008; Jaeggi, Studer-Luethi, et al., 2010) and the elderly, with effect sizes ranging between 0.98 and 1.12 (Borella, Carretti, Riboldi, & De Beni, 2010; Carretti, Borella, Zavagnin, & De Beni, 2012). There is also evidence that a

WM training may change the pattern of the subject's biological activity in aspects assumed to be related with intellectual functioning (e.g., Jaušovec & Jaušovec, 2012; Söderqvist et al., 2012).

Other studies that did not find an effect on intelligence, though, suggest that the observation of a positive effect is related to the presence of specific boundary conditions (Chooi & Thompson, 2012; Owen et al., 2010; Redick et al., 2012; for a review, see Melby-Lervåg & Hulme, 2012, and Shipstead, Redick, & Engle, 2012). These different results could be due, for example, to the role of individual differences, as the effects have been mainly found in children and aged people and some individuals seem to derive more advantage from this training than others (Jaeggi, Buschkuhl, Jonides, & Shah, 2011).

However, at the theoretical level, the observed improvements in WM and intelligence do not necessarily mean that the basic abilities have been modified, as the improvements could only be related with the ability to cope with cognitive tasks. More generally, improvements in WM could result in an improved capacity to use it well, rather than an increased WM capacity, and the transfer effects on intelligence could result from better use of WM and related attentional functions in the intelligence tasks. This conclusion is in agreement with the large body of studies showing that performance in intelligence tests is the combined product of abilities that are biologically rooted or acquired through experience as in the case of strategic control of the to-be-carried out processes (Cornoldi, Giofrè, & Martini, 2012; Nisbett et al., 2012). This hypothesis also accords with Klingberg's (2010) conclusion that WM improvement primarily occur in control processes and with the observations that the effects of WM training mainly happen in individuals who need to be trained to use WM well, as the benefits in WM are greater for low-performing subjects (Holmes, Gathercole, & Dunning, 2009). This result is further supporter by the evidence that the improvement in analogical reasoning, which is highly related to fluid intelligence, is related to the initial level of ability, as it may especially interest low ability children (Stevenson, Hickendorff, Resing, Heiser, & De Boeck, 2013).

WM training, therefore, seems effective and should be purposefully administered, especially with poorly performing individuals, in efforts to improve not only intelligence but also the performance in various intellectual tasks in which WM has a critical role, such as reading comprehension, problem-solving, reasoning, and text production. These competencies can be considerably enhanced (Clarke, Snowling, Truelove, & Hulme, 2010; García-Madruga et al., 2013), offering further support to the hypothesis that abilities related both to WM and intelligence can be modified (for a different argument, see Shipstead, Hicks, & Engle, 2012).

Conclusions

In conclusion, the recent cognitive research has produced a substantial change on how the construct of intelligence is treated in Psychology, adding to the traditional psychometric and developmental perspectives a new perspective exploring the cognitive mechanisms underlying intellectual functioning. In this paper we argued that, between these mechanisms, important evidence shows that WM is particularly crucial especially when its most active components are considered. This evidence appears relevant not only at a theoretical level, but also for its practical implications. In this paper we have in particular considered the implications for assessment and treatment. Concerning assessment, we have argued that the WM component must be more explicitly taken into account when intelligence is measured, as it is in fact proposed in the last version of the WISC battery. Concerning treatment, we think that the possibility of proposing WM trainings must not be dismissed on the basis of the fact that evidence for the efficacy of WM training is highly debated (Shipstead, Hicks et al., 2012), if – at least sometimes - they produce important effects. The goal of improving intellectual abilities is so important, especially for low functioning individuals, that any plausible intervention strategy must be taken into account.

Despite the evidence here reviewed about the importance of WM in intelligence-related issues, some considerations also urge caution before drawing too strong conclusions. In particular, it must be

noticed that the correlation between WM and intelligence is far from perfect (Ackerman et al., 2005). This result offers support to the assumption that WM and intelligence, despite their connections, remain two different constructs (Engle et al., 1999; Kane et al., 2004; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002), and suggests that the relationship should be more deeply considered. In the present paper we have argued that models distinguishing between different components of WM can better describe the relationship between WM and intelligence, but it should also be explored whether models distinguishing between different components of intelligence add further explanatory power, as for example in the case of the distinction between fluid and crystallised intelligence (Martínez, & Colom, 2009). It should be also observed that the argument that differences in speed and executive tasks might be due to differences in WM can also partly run the opposite way: High speed or executive abilities could create high WM performance. Finally, the hypothesis that WM is highly related with intelligence meets problems in the case of some individuals and groups of individuals have WM problems without intelligence impairments. A particularly representative case is intelligent individuals with ADHD syndrome who present deficits in high attentional-control WM tasks. We have recently showed that the WM performance of these children is related not only to fluid intelligence but also to a specific control component that is independent of intelligence and is poor in ADHD (Cornoldi et al., 2012). This suggests that WM performance is related not only with general abilities, but also with specific components.

These critical observations do not question the general observation that WM is a critical concept in explaining intellectual functioning but show that the distinction between the two concepts of WM and intelligence must be maintained and that their relationship is subject to some limitation.

Footnote

¹ The keywords we used were intelligence, emotional intelligence, multiple intelligences, artificial intelligence, cognitive assessment, gifted, intellectual development, intelligence quotient, IQ, mental age, and reasoning.

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