

**Working memory mediates the effects of gestational age at birth on expressive language development in children**

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### Abstract

**Objective:** This study tested the role of temporary memory, measured by phonological short-term memory (pSTM) and verbal working memory (vWM), as a mediator of the effect of three putative risk factors (i.e., socioeconomic status, home literacy environment, birth gestational age) upon expressive and receptive language.

**Method:** A community-based sample of 646 Italian children aged 6-11 years was assessed with a comprehensive battery of language and cognitive tests. A mediation analysis was used to examine whether memory mediates environmental/biological effects on language.

**Results:** The results demonstrated a developmental cascade of effects, whereby the duration of pregnancy drives WM functioning that, in turn, may affect expressive linguistic outcome

**Conclusion:** Treatments focused on vWM, specifically to preterm children, may improve their language development, with enduring consequences on educational and psychosocial outcomes.

*Keywords:* memory, language, environmental/biological factors, mediation

### Public Significance Statements

- The results demonstrated a developmental cascade of effects, whereby the duration of pregnancy drives WM functioning that, in turn, may affect expressive linguistic outcome
- Treatments focused on vWM, specifically to preterm children, may improve their language development, with enduring consequences on educational and psychosocial outcomes.

## **Working memory mediates the effects of gestational age at birth on expressive language development in children**

Language is a complex function acquired during the first years of life; while formal instruction is not necessary, infants need to interact with the linguistic environment right after birth to ensure proper development (Kuhl, 2010). The aetiology underlying the acquisition of language has been widely explored (Stromswold, 2006). A number of twin studies have been conducted, which show that although the etiology of language is significantly explained by genetic factors (Dale, Dionne, Eley, & Plomin, 2000; Dale, Harlaar, Hayiou-Thomas, & Plomin, 2010; Dionne, Dale, Boivin, & Plomin, 2003), environment plays a significant role, contributing up to 30% of the variance in expressive language, and to a lesser extent to receptive skills (Stromswold, 2001). However, while the association between environment and language development is well-established, it is still an open question whether and which cognitive systems are implicated in and underpin this association. This might be crucial for tracing children who are at heightened risk of language impairment and plan timely and focused support. As such, the overall goal of this study is to examine the extent to which the effects of memory may mediate well-known influences of environmental factors on language development.

### **Associations Between Environmental/Biological Factors And Language**

Candidate pathways from environment to language development include sociodemographic factors, primarily socioeconomic status (SES) and home literacy environment (HLE; Hart & Risley, 1992; Hackman & Farah, 2009), and biological factors, such as birth gestational age (Shapiro-Mendoza & Lackritz, 2012). In particular, SES is a well-established predictor of language at many different stages of development and it has been associated in all domains of linguistic competence, but especially in lexical-semantic knowledge and phonological awareness (Noble, McCandliss, & Farah, 2007). SES

associations have been found both with expressive and receptive language. For example, high-SES children had larger productive vocabularies than the mid-SES children.

Furthermore, SES explained individual differences in performance on a variety of tasks that were designed to tap specific neurocognitive systems underpinning linguistic receptive abilities (Noble et al., 2007).

Early measures of HLE, for example the number of books at home, storybook reading frequency, letter-based activities, singing and playing language games, are also significantly predictive of language development, especially expressive vocabulary and fluency, and have lasting influences during the early school years and on reading acquisition (Hoff & Tian, 2005; McKean et al., 2015; Roberts, Jurgens, & Burchinal, 2005; Wood, 2002). In a longitudinal study of English-speaking children schooled in French and followed up from kindergarten to the early school years, HLE was specifically associated with growth in English vocabulary, providing strong support for the relevance of domestic versus other sources of literacy stimulation (Sénéchal & LeFevre, 2014).

Another relevant source of environment-related variability in language development (including vocabulary, receptive grammar and phonological processing) is the birth gestational age (Northam et al., 2012).

Preterm births, those born before 37 weeks of gestation, are at increased risk of mortality and are more likely to have long-term neurological and developmental disorders than at-term births, and remain vulnerable to a wide range of complications, including respiratory, gastrointestinal, hearing, and vision problems, and affections of the immune and central nervous system (Beck et al., 2010).

Up to 38% of preterm children without neonatal brain injury experience various degrees of impaired language development, which is associated with alterations in the

structural and functional expressive and receptive connectivity in the major language brain areas (Wilke, Hauser, Krägeloh-Mann, & Lidzba, 2014).

While very preterm children (born before 32 weeks of gestation) are the focus of most outcome research, language impairments have also been reported in moderate to late preterm children (born 32 to 36 weeks of gestation) and who represent the majority of preterm births (Huddy, Johnson, & Hope, 2001; Kerstjens, de Winter, Bocca-Tjeertes, ten Vergert, Reijneveld, & Bos, 2011; McGowan, Alderdice, Holmes, & Johnston, 2011; Shapiro-Mendoza & Lackritz, 2012).

### **Associations Between Memory And Language**

Substantial evidence shows that memory skills, specifically those that refer to the temporary storage of verbal information, are associated with language development. Verbal temporary memory includes phonological short-term memory (pSTM), where auditory material is held passively and then immediately reproduced orally, and verbal working memory (vWM) where the retained information is manipulated over brief periods of time to guide an immediate oral response.

Measures of forward and backward digit span are among the oldest and most widely used neuropsychological tests of verbal temporary memory (Aben, Stapert, & Blokland, 2012), tapping respectively pSTM (Richardson, 2007) and vWM processes (for a meta-analysis see Owen, McMillan, Laird, & Bullmore, 2005). While some evidence suggests that pSTM and vWM are basically overlapping processes, most studies support them as two different yet collaborative mechanisms (for a thorough discussion on this issue, see Aben et al., 2012). Indeed, the prefrontal cortex (PFC) is involved in both pSTM and vWM (Owen et al., 2005); however, ventrolateral PFC has been associated with the maintenance of information (pSTM), whereas mid-dorsolateral PFC and the superior parietal cortex are additionally recruited when manipulation is required (vWM).

Both components of temporary memory contribute to language acquisition (Baddeley, 2003; Baddeley, Gathercole & Papagno, 1998), appear anatomically linked to the language circuit (Buchsbaum & D'Esposito, 2008), and share environmental risk factors with language (Evans & Schamberg, 2009; Farah et al., 2006; Hackman et al., 2014; Heinonen et al., 2015; Noble et al., 2007; Peterson, Pennington, Samuelsson, Byrne, & Olson, 2013; Sarsour, Sheridan, Jutte, Nuru-Jeter, Hinshaw, & Boyce, 2011), suggesting that temporary memory might mediate and account for, at least in part, some environment-related disparities in language development. Indeed, growing evidence suggests that both pSTM and vWM correlate with receptive and expressive skills, mediate the acquisition of new vocabulary (especially with a high load of unfamiliar sounds), and are impaired in children with specific language impairments (Archibald & Gathercole, 2006; Ellis Weismer, Evans, & Hesketh, 1999; Gathercole, Hitch, Service, & Martin, 1997; Marini, Gentili, Molteni, & Fabbro, 2014; Michas & Henry, 1994). For example, in Gathercole et al., (1997), both pSTM and vWM were significantly associated with a composite score of expressive and receptive language at 5 and 13 years of age. At the same time, articulatory skills were related to vWM, but not with pSTM, suggesting that the former might specifically subserve expressive language.

Interestingly, recent event-related functional imaging studies show that an area located in the Sylvian–parietal–temporal junction (Spt), that is, the superior temporal gyrus, is involved in temporary memory tasks (Buchsbaum, Hickok, & Humphries, 2001; Buchsbaum, Olsen, Koch, & Berman, 2005; Buchsbaum et al., 2011; Hickok, Buchsbaum, Humphries, & Muftuler, 2003). As Spt had been previously proposed as the interface for the integration of sensory and motor representations of language (Hickok & Poeppel, 2004; 2007), perception, temporary memory storage, and production of verbal information might all, at least in part, share the same anatomical substrate, supporting temporary memory as an

inherent capacity of the language circuit (Buchsbaum & D'Esposito, 2008) rather than a separate entity as originally conceptualized (Baddeley, 2001).

### **Memory As A Mediator Between Environmental and Biological Factors And Language**

Some evidence shows that environmental and biological factors relevant for language development also exerts a direct influence on memory. Verbal temporary memory was found impaired in preterm individuals in a longitudinal cohort of 919 adults from the Helsinki Birth Cohort Study, supporting memory as a target of direct effects of prematurity and suggesting that such effects may have long-lasting consequences (Heinonen et al., 2015). Robust associations have also been found between both SES and HLE, and temporary memory (Evans & Schamberg, 2009; Farah et al., 2006; Hackman et al., 2014; Noble et al., 2007; Peterson, et al., 2013; Sarsour et al., 2011). For example, SES in children attending primary school accounted for 5.5% of the variance in vWM (Noble et al., 2007). Similar correlations between SES and vWM have been shown in middle childhood (Sarsour et al., 2011) and in adolescence (Hackman et al., 2014; Waber et al., 2007), suggesting enduring effects. Interestingly, Sarsour et al. (2011) showed that the association between SES and vWM was specifically mediated by elements of the child's home environment, including both parenting variables (i.e., responsivity and family companionship) and material resources available (i.e., enrichment activities), suggesting that some specific domains of home environment are crucial to the mechanism linking SES and vWM.

While all the above evidence provides sufficient support to test verbal temporary memory as a mediator of environmental/biological effects upon language, it is still not clear which memory components might be involved. Experimental studies of language and memory often focus solely on either one of the two components of temporary memory (i.e.,



pSTM or vWM), thus limiting the possibility to disentangle the potential specific contribution of each temporary memory components upon language outcomes.

### **Objectives**

In this study we tested verbal temporary memory (i.e., vWM and pSTM) as a mediator of the effect of the individual differences in three well-replicated environmental (i.e., SES, HLE) and biological (i.e., birth gestational age) factors upon language outcomes in a community-based sample of 646 Italian children aged from 6 to 11 years old.

In this study we tested verbal temporary memory (i.e., vWM and pSTM) as a mediator of the effect of the individual differences in three well-replicated environmental (i.e., SES, HLE) and biological (i.e., birth gestational age) factors upon language outcomes in a community-based sample of 646 Italian children aged from 6 to 11 years old.

We addressed two major questions. First, with respect to language outcome, are there two distinguishable targets of environmental/biological effects, namely expressive and receptive skills? Confirmatory factor analysis (CFA) was used to examine this issue and to test the model's suitability to our dataset. Second, does temporary memory mediate environmental/biological effects on language outcome? A mediation model using SEM was used to examine this latter question, providing model fit information about the consistency of the mediation hypothesis and evidence for the plausibility of the causality assumptions (Bollen & Pearl, 2012).

To our knowledge, this is the first study that explicitly addresses the hypothesized direction of association links between environmental/biological predictors, verbal temporary memory, and language outcome using the SEM framework.

### **Methods**

## Participants

The target population of this study consisted of Italian-speaking children aged 6-11 years recruited in 5 Italian school districts. The target sample was formed by 1,422 children, 967 from public and 455 from private schools ( $M_{\text{age}} = 8.22 \pm 1.17$ ; female:male ratio = 0.9). Meetings were scheduled at each school district to explain the study's purpose, required time commitment, and eligibility criteria to parents/guardians. Of target families, 57.6% declared availability to take part in the study yielding a final sample of 819 children. Participants and non-participants did not differ significantly on child's age and gender, and school of attendance. Written informed consent was obtained from all parents prior to testing.

A total of 646 children were found eligible for the study after the application of the following exclusion criteria: (1) Inability to complete at least 50% of direct testing ( $n = 9$ ), (2) Having certified visual, hearing, intellectual or motor disabilities, or scores on both WISC-III subtests vocabulary and block design  $< 4$  ( $n = 29$ ). In addition, children not belonging to families of Italian mother tongue for at least one generation ( $n = 135$ ) were excluded because of language limitation and to avoid possible bias due to native language status.

## Materials

The participants completed a direct testing of cognitive and language tasks, whereas their caregivers were asked to fill out a 1-hour *ad hoc* questionnaire that provided information on demographic, socio-economic, obstetric and gynecological data, and the Home Literacy Environment Questionnaire (Marjanovič-Umek, Podlesek, & Fekonia, 2005) that were sent to them by mail. The direct testing typically took place in a quiet room at school in the morning of regular schooldays, lasted around 1.5 hours, and was administered by one of three trained examiners with extensive experience in administering standardized assessments to children for research purposes.

**Cognitive assessment.** Cognitive tasks were the vocabulary, block design, and digit recall subtests of the Wechsler Intelligence Scale for Children-III (Wechsler, 2006).

Vocabulary and block design were used as proxy measures of Intelligence Quotient (IQ) on the basis of their high correlations ( $r$ ) with verbal and performance IQ ( $r = .82$ , and  $r = .73$ ), respectively (Wechsler, 2006). Scores were standardized based on age norms ( $M = 10$ ;  $SD = 3$ ). For each participant, vWM was assessed in terms of performance at the backward digit recall subtest of the Wechsler Scales. Similarly, performance at the forward digit recall subtest of the Wechsler Scales was considered as a measure of pSTM. Memory measures were transformed into age-standardized z-scores ( $M = 0$ ;  $SD = 1$ ), based on our sample mean in each year level.

**Language assessment.** Language assessment comprised four tasks tapping naming and semantic fluency (expressive language) and lexical and syntactic comprehension (receptive language). Naming, semantic fluency and lexical comprehension were measured by administering the corresponding subtests of the ‘Batteria per la valutazione del linguaggio in bambini dai 4 ai 12 anni – BVL\_4-12’ (Battery for the assessment of language in children aged 4 to 12 years; Marini, Marotta, Bulgheroni, & Fabbro, 2015). In the naming subtest, participants were asked to name a total of 67 visually presented stimuli (e.g., objects, colors, verbs) as rapidly and accurately as possible; the total score reflects the sum of correct answers (max score: 67). In the semantic fluency task, participants were asked to produce in 60 seconds as many words as possible belonging to two semantic categories (i.e., ‘animals’ and ‘objects in the house’); the total score reflects the sum of appropriate words produced in due time. In the lexical comprehension task, participants were asked to identify which out of four pictures (one target, one phonological, one semantic and one unrelated distracter) corresponded to the meaning of the word uttered by the examiner. The total score reflects the sum of correct answers (max score: 42).

Finally, syntactic comprehension was assessed by administering the Token test for children (De Agostini et al., 1998), which consists of a list of 21 commands of increasing syntactic complexity. These require the participants to arrange a set of 20 tokens of different shapes (e.g., circles, squares, etc...), colors (e.g., red, blue) and size (either big or small) according to the requests formulated by the examiner. The total score reflects the sum of correct arrangements (max score= 21). All linguistic measures were standardized on age-based general population norms (Marini et al., 2015; De Agostini et al., 1998), with mean of 0 and standard deviation of 1.

**Environmental and biological factors.** Environmental and biological predictors were derived from the questionnaires compiled by parents and comprised birth gestational age, SES, and HLE. Birth gestational age was calculated from the date of the last menstrual period as reported in obstetrical clinical records. Family SES was scored according to the Hollingshead 90-point scale (Hollingshead, 1975), whereby a score ranging 10–90 was assigned to each parental job, and the higher of two scores was used when both parents were employed (Nobile et al., 2007; Riva, Marino, Giorda, Molteni, & Nobile, 2015). HLE was obtained from the Home Literacy Environment Questionnaire (Marjanovič-Umek et al., 2005). The questionnaire contains a total of 33 statements describing the ways in which parents talk to their children (e.g., “When talking to my child I use grammatically correct sentences” or “I try to explain things, which I believe my child understands”) and the different literacy activities in which they involve them (e.g., “I visit the library with my child” or “I read to my child whenever she wants me to”). Parents used a 3-point scale to mark the frequency of the behaviour described or activity performed with the child (i.e., 0= *never*; 1= *sometimes*; 2= *usually*). A higher score indicates a higher quality of a child’s HLE.

### **Statistical Analyses**

Descriptive statistics and Pearson's bivariate correlation analyses were performed using SPSS, Version 21.0. To investigate the contribution of environmental and biological predictors to language and the potential role of pSTM and vWM as mediators, we used mediation analysis (Fritz & MacKinnon, 2007). The mediation model tested the hypothesis that language outcomes would be explained by a sequence of potentially associated effects involving environmental and biological predictors of memory. Specifically, the following was proposed: Environment/biological putative risk factors (birth gestational age, SES and HLE) → memory (vWM and pSTM) → language (expressive and receptive). We then defined the measurement model which best describes the relationships between the dependent variables (Mueller & Hancock, 2008).

To examine whether expressive and receptive components of language were distinguishable processes and to test the two-component outcome model's applicability to the mediation model, a main two-factor CFA model was evaluated. To accomplish the CFA and the mediation analysis, we used SEM as implemented in the MPLUS software package (Muthen & Muthen, 2014). Mediation effects were quantified using the bias-corrected 5000 bootstrap technique to assess non-normality in the product coefficient (Fritz & MacKinnon, 2007). Confidence intervals (95% CI) that do not contain zero indicated significant indirect effects (MacKinnon, Lockwood, & Williams, 2004; Taylor, MacKinnon, & Tein, 2008; Tofighi & MacKinnon, 2011). This method offers the best power, confidence interval placement, and overall control for Type I error (Williams & MacKinnon, 2008). SEM simultaneously models all paths, giving more powerful, accurate and robust estimation of mediation effects (Iacobucci, Saldanha, & Deng, 2007) than more traditional tests based on sequential regressions, especially when more than one mediator is implemented in the model.

SEM is used to examine relationships among variables and test theoretical causal models when multiple variables are involved. Thus, path analysis can be reduced to the

solution of several multiple linear regression analyses and it is used to determine if a multivariate set of data fits well with a particular a priori model. All of the relationships among variables in the model are tested together and all of the paths can be compared with each other in terms of the degree of importance of each variable (Pedhazur, 1982).

While there is no golden rule for the assessment of model fit, reporting a variety of indexes is advisable (Crowley & Fan, 1997) because different indexes reflect different aspects of model fit. To evaluate the goodness-of-fit of the model, we used the following fit indexes: Chi-Square, Root Mean Square Error of Approximation (RMSEA), the comparative fit index (CFI) and Standardized Root Mean Square Residual (SRMR). The Chi-square is a test of model misspecification that assesses the difference in magnitude between the sample and the model estimated variance/covariance matrices. The significance value of Chi-square is sensitive to large sample sizes and easily produces significant results (Bollen, 1989; Kelloway, 2015). In order to address these limitations of the Chi-square statistic, several fit indices have been proposed. The RMSEA – which is one of the most often used indices - is an index that takes into account the complexity of the model (Kline, 2011). Values of RMSEA less than or equal to 0.05 indicate a good fit (Browne & Cudek, 1993). A usual practice is to provide the 90% confidence interval (CI) for the RMSEA, which includes the sampling error associated with the estimated RMSEA. A lower bound of 90% CI less than 0.05, as well as an upper limit less than 0.08, indicate a good fit (Browne & Cudek, 1993). The SRMR is a standardized version of the RMSEA and it represents the average residual value derived from the fit of the model covariance matrix to the sample covariance matrix. SRMR values equal to or less than 0.08 are considered good (Hu & Bentler, 1998). Finally, the CFI is a comparative fit index that measures the improvement of overall fit of the model by comparing the hypothesized model with a more restricted one, which specifies no relations

among variables. Values of CFI greater than or equal to 0.95 indicate a good fit (Whitley & Kite, 2013).

Since data across all observation are missing completely at random (Little's MCAR  $\chi^2= 97,77$ ;  $DF= 87$ ;  $p= .202$ ), missing data were taken into account using the Full Information Maximum Likelihood estimation, which is the default estimator, to allow the use of all available data with the inclusion of subjects with missing data. We used the method of maximum likelihood that tolerates departures from normality, especially if skewness values are below  $|2|$  and kurtosis values are below  $|7|$  (West, Finch, & Curran, 1996). Level of significance was set at  $p \leq 0.05$ .

## Results

Descriptive statistics of cognitive and language measures and environmental/biological factors are shown in Table 1. Descriptive statistics of gender, IQ measures and environmental/biological factors as a function of age are reported in Table S1.

We examined the correlations among cognitive and language measures, and among putative risk factors (Table 2). Correlations were moderate between language measures (range  $r= .20$ -.29), low between language and pSTM and vWM ( $r= .03$ -.15), and moderate between pSTM and vWM ( $r= .30$ ), and between language and IQ measures (range  $r= .13$ -.35). Finally, no significant correlations among putative risk factors were found, except for HLE and SES, for which a significant, but low, correlation was observed ( $r= .18$ ).

### **Confirmatory Factor Analysis: Expressive And Receptive Latent Constructs For Language**

The CFA model tested whether the shared variance among measured dependent linguistic variables was attributable to two latent correlated constructs (i.e., expressive and receptive). The results of the CFA for the four language measures are shown in Table S2, with the factor loadings for each measure. The standardized factor loadings ranged from .41

to .54, and were all significant ( $p < .05$ ). The correlation between the two latent factors was .33. Fit statistics for the CFA model [ $\chi^2(3) = 6.12, p = .19, RMSEA = .03, CI(90\%) = .000-.071, CFI = 1.00, SRMR = .019$ ] indicated a good fit to the data, supporting two distinct, yet correlated, pathways for expressive and receptive language outcomes, and the applicability of the two-factor CFA to test the mediation model.

### **Mediation Model: pSTM And vWM As Mediators Between Environmental/Biological Predictors And Language Latent Factors**

We next used SEM to test the mediation model depicted in Figure 1, which assumes that three environmental/biological factors (i.e., birth gestational age, HLE and SES) contribute to pSTM and vWM that in turn affect two latent language factors (i.e., expressive and receptive).

The mediation model provided a good fit to the data [ $\chi^2(11) = 24.68, p = .01; RMSEA = .046, CI(90\%) = .021-.070; CFI = .96; SRMR = .025$ ] and explained 14.4% and 14.0% of the variance in the expressive and receptive factors, respectively. Standardized estimates of path coefficients are depicted in Figure 1 and all the standardized direct effects in the model are reported in Table S3. The only significant indirect effect was the path from birth gestational age to the expressive factor via vWM ( $\beta = .031; SE = .014; 95\% CI = .003-.058; p = .030$ ). pSTM-mediated effects of birth gestational age upon both expressive and receptive language were not significant. All other environmental factors (i.e., HLE and SES) had no indirect effects, either mediated by vWM or pSTM, upon either expressive or receptive language. Table 3 shows standardized indirect effects from predictors to expressive and receptive factors via vWM and pSTM, using 5000 bootstrapping analyses and bias-corrected 95% CI (Williams & MacKinnon, 2008).

To investigate qualitatively different path models, birth gestational age was split into two classes, namely 'moderate preterm' (32-36 gestational weeks) and 'full-term' (37-42



gestational weeks). This new model provided a good fit to the data ( $\chi^2(11) = 26.20, p = .006$ ; RMSEA = .048, CI (90%) = .025-.073; CFI = .95; SRMR = .026). In particular, the indirect effect from birth gestational age to expressive language via vWM remained significant and was even stronger ( $\beta = .038$ ; SE = .016; 95% CI = .006-.069;  $p = .021$ ), suggesting that moderate preterm children showed more vWM difficulties, and in turn expressive language impairments, than full-term children.

The mediation model yielded also several significant direct effects. First, as shown by the path coefficient from HLE to expressive ( $\beta = .16, p = .012$ ) and from SES to both expressive and receptive factors ( $\beta = .18, p = .011$  and  $\beta = .19, p = .003$ , respectively), children from a disadvantaged socioeconomic and literacy milieu have poorer performance on language tasks. Second, we found significant paths between birth gestational age and vWM ( $\beta = .12, p = .003$ ) and between SES and both vWM and pSTM ( $\beta = .09, p = .027$ , and  $\beta = .10, p = .011$ , respectively), all in the expected directions. Third, we found that there was a significant correlation between pSTM and vWM ( $r = .30; p < .001$ ), and that both measures had significant direct effects on language. Most interestingly, these latter effects were dissociated for pSTM and vWM, as pSTM is associated with receptive ( $\beta = .17, p = .020$ ) but not expressive skills ( $\beta = .02, p = .799$ ), while vWM is associated with expressive ( $\beta = .26, p = .001$ ) but not receptive abilities ( $\beta = .13, p = .080$ ).

To control for the effect of age, we repeated the same analyses considering age at testing as covariate. The mediation model provided good fit to the data [ $\chi^2(21) = 36.60, p = .02$ ; RMSEA = .036, CI (90%) = .014-.054; CFI = .96; SRMR = .025] and both the direct and the indirect effects remained significant (indirect effect:  $\beta = .024$ ; SE = .012; 95% CI = .004-.054;  $p = .042$ ).

Finally, given the low-to-moderate correlation between language and IQ ( $r = .21$ ), we repeated the mediation model controlling for IQ block design. No significant IQ effect was

found in tested model. Similarly, since language development has been reported to vary according to sex (for a review see Wallentin, 2009), we repeated the same mediation analysis considering sex as covariate. No significant sex effect was found and findings were overlapping with the mediation model without this covariate (data available upon request).

### **Discussion**

The present study aimed to disentangle the complex relation between three environmental/biological factors that have been described to contribute to language development (i.e., birth gestational age, SES, and HLE), the ability to process verbal information in pSTM and vWM and linguistic skills. After identifying the two latent factors underlying the linguistic performance of children involved in the study (i.e., one expressive and one receptive), we found one significant indirect path linking the number of birth gestational age to the expressive factor via vWM and three significant direct paths proceeding from HLE to expressive skills and from SES to both expressive and receptive factors. Finally, we detected a particularly intriguing pattern in the relation between measures of vWM and pSTM and performance on linguistic tasks: pSTM was associated with receptive but not expressive skills, whereas vWM was associated with expressive but not receptive abilities. The implications of these findings are discussed below.

#### **The CFA model: expressive and receptive language**

The latent factor analysis (CFA) allowed extracting the common variance that was shared among the different tasks tapping the linguistic skills of participants, minimizing task specific variance and measurement errors. This provided us with rather reliable, accurate, and best fit measures for the dependent variable in our mediation model (Friedman, Miyake, Corley, Young, Defries, & Hewitt, 2006). These constructs are in harmony with the dual route model of auditory processing (Hickok, 2001; Hickok & Poeppel, 2004; 2007), which posits that sensory input to the superior temporal cortex follows two anatomically separated

but functionally connected streams, that is a ventral pathway, which maps phonological representations of speech into lexical conceptual representations (receptive language), and the dorsal pathway, which maps into articulatory motor representation (expressive language).

### **The mediation role of vWM**

Using SEM and the mediation analysis, we showed that verbal temporary memory was a significant mediator of the contribution of birth gestational age to language. The mediating effect was driven exclusively by vWM, and it specifically contributed to the expressive language factor. pSTM-mediated effects of birth gestational age on both language factors were not significant, as well as direct effect of birth gestational age on receptive and expressive language, suggesting that birth gestational age specifically contributed to expressive language and that vWM completely mediated this relationship.

Most research to date has focused on children born extremely preterm (born before 32 weeks), suggesting that these children show, among other neurosensory or motor problems, delays in both receptive and expressive language. In the present study, we have shown that infants born between 32 and 37 weeks are still at high risk for cognitive and language difficulties in the absence of major neurosensory or motor impairments compared to those infants born full term.

Pre- and full-term infants differ in the length of intrauterine experience, which has been related to different maturational brain patterns at birth (Gonzalez-Gomez & Nazzi, 2012). The ability to generate and keep memory traces as long as needed and to manipulate them might be affected by shorter gestational age and this might determine life-long changes in the ability to learn language, among others. Indeed, infants approach language during a sensitive and critical period within the first year of life with a set of initial perceptual abilities that are necessary for language acquisition (Kuhl, 2004). During the initial perceptual phase (sensory phase), infants build up their linguistic repertoire and commit to memory storage the

characteristic features of language. The perceptual characteristics stored in memory serve as guides for production (Kuhl, 2004). Recently, Pitcher, Goldhaber, Duchaine, Walsh, and Kanwisher (2012) have shown that an impairment in the ability to generate and keep memory traces might be the mechanistic link to the developmental deficits that significantly affect preterms. By using repetitive transcranial magnetic stimulation (rTMS), this study examined in preterm and full-term adolescents long-term-depression (LTD)-like neuroplastic changes, which are key cellular mechanisms underlying memory (for review, see Feldman, 2009). Compared with term-borns, preterm adolescents had reduced LTD-like neuroplasticity in response to brain stimulation, suggesting that the mechanisms underlying memory formation in preterm individuals were impaired (Pitcher et al., 2012).

As an alternative explanation, neuroimaging studies have shown that preterm infants have subtle brain lesions such as diffuse white matter abnormalities, which are linked with both later cognitive and language impairments (e.g., Kurata et al., 2016; Woodward, Clark, Bora & Inder, 2012). Even if these abnormalities are most common in very preterm children (< 32 gestational weeks), it could be the case that memory and expressive language difficulties co-exist due to common underlying neural pathology. Future longitudinal studies are needed to better examine the effect of prematurity on the relationship between cognitive skills and language.

### **The role of SES and HLE**

Surprisingly, in our study, temporary memory had no unique mediating effects for either SES or HLE. Although direct effects of both SES and HLE upon language have been described (Tomblin, Smith, & Zhang, 1997), two other explanations for this finding are plausible. First, the contribution of environments to language skills might be mediated by other neurocognitive systems that were not tested in our sample, such as auditory processing or executive functions, for which both associations with language development (Benasich,

Thomas, Choudhury & Leppanen, 2002; Cantiani et al., 2016; Hackman & Farah, 2009) and socio-demographic factors (Stevens, Paulsen, Yasen, & Neville, 2015; Hackman, Gallop, Evans, & Farah, 2015) have been described. An alternative explanation could be that the relation between SES and HLE and language development is mediated by more proximal familial factors that were not tested in our sample, such as parenting style or mother-child dyadic interactions (Perkins, Finegood, & Swain, 2013).

Several significant direct effects emerged that were in line with the premises of the mediation model and corroborated our hypotheses. Regarding the environmental factors, our data showed that SES and HLE are directly associated with language, replicating previous findings (Farah et al., 2006; Hackman & Farah, 2009; Hart & Risley, 1992; Hoff & Tian, 2005; McKean et al., 2015; Noble et al., 2007; Roberts et al., 2005; Sénéchal & LeFevre, 2014; Wood, 2002). Moreover, consistently with the literature across kindergartners, first graders, and preadolescents (Evans & Schamberg, 2009; Farah et al., 2006; Hackman et al., 2014; Sarsour et al., 2011; Waber et al., 2007), disadvantaged SES was related to impaired temporary memory.

### **The direct effects of pSTM and vWM**

Finally, we found that pSTM and vWM had significant direct selective effects on, respectively, receptive and expressive language. These data suggest that, while a gross effect of temporary memory upon language has been widely demonstrated (Baddeley, 2003; Baddeley, Gathercole & Papagno, 1998; Gathercole, Hitch, Service, & Martin, 1997), specific pathways might as well exist (Acheson, Hamidi, Binder, & Postle, 2011; Buchsbaum & D'Esposito, 2008; Jackson, Leitao, & Claessen, 2016).

Previous research had suggested that pSTM capacity plays a crucial role in receptive language, and it represents an important source of individual differences in comprehension ability. Indeed, children with language impairment often experience word-learning

difficulties, which are suggested to originate in early stage pSTM-mediated fast mapping of sounds (Baddeley et al., 1998; Ellis & Sinclair, 1996).

On the other hand, evidence from neuroimaging and rTMS literature (Acheson et al., 2011; Buchsbaum & D'Esposito, 2008) links expressive language and vWM processes. It has been shown that conduction aphasia, which is characterized by expressive symptoms such as speech errors and naming difficulties, is associated with a specific damage of area Spt, which is the interface for the integration of sensory and motor representations of language and it is critical for vWM (Buchsbaum et al., 2011).

### **Limitations**

As a concluding remark, we would like to point to some limitations of this study.

First, as this is a cross-sectional study, we believe that a longitudinal design might better clarify the relationship among environment, memory and language outcomes over time. Second, although fast to administer, the assessment of environmental and biological factors via questionnaires, especially the retrospective measures compiled by parents and households, might have biased the reliability of the collected data. However, in order to preserve a sufficiently large number of participants in face of a time-consuming (1.5 hours) direct assessment of each child, this appeared a viable compromise.

Taken together, the mediation model explains 14.4% of the variance in receptive and 14.0% in expressive language. Such limited ability to explain variance by measured predictors has been extensively reported (Henrichs et al., 2011; Harrison & McLeod, 2010; Reilly et al., 2007; Zubrick et al., 2007), and is consistent with the view that individual differences in language skills are caused by a large amount of factors. Although we were aware that a variety of factors were relevant for language development, in this study we opted to limit model testing only three among the most replicated risk factors (i.e., SES, HLE and birth gestational age) in order to preserve acceptable power estimates. Future research should

test in larger samples the concurrent role of a wider range of environmental factors, such as parenting, parental educational level, siblings interaction (Ghassabian, Rescorla, Henrichs, Jaddoe, Verhulst, & Tiemeier, 2014; Henrichs et al., 2011; Reilly et al., 2007; 2010).

This result supports the importance of including temporary memory in explaining a sizable proportion of variance in language development. Specifically, pSTM and vWM account for an additional 6.0% and 6.4% proportion of variance in expressive and receptive language latent factors. Even if forward and backward digit span from the WISC-III are widely used neuropsychological tests of verbal temporary memory (e.g., Guarini et al., 2016; Marini, Gentili, Molteni & Fabbro, 2014; Pisoni & Clearly, 2003; Pisoni, Kronenberg, Roman & Geers, 2011), some authors have questioned their reliability in measuring respectively short term and working memory processes (e.g., Alloway, 2007; Reynolds, 1997). In this study, we reasoned that the forward and backward digit span were the best measures given the large size of our sample and the school setting. However, future studies are needed to address the robustness of our findings using more sophisticated, experimental tasks.

### **Conclusions**

In summary, the model demonstrates a potential developmental cascade of effects, whereby the duration of gestation drives vWM functioning that, in turn, may affect linguistic outcomes, mainly expressive language.

This study may open new perspectives for intervention. Treatments focused on vWM skills might improve the prognosis of language development in preterm children, with enduring consequences on educational and psychosocial outcomes.

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Table 1

*Descriptive statistics of cognitive, language and environmental factors (n= 646)*

	Min	Max	M (SD)	Skewness	Kurtosis
<b>IQ<sup>a</sup></b>					
<b>IQ Vocabulary</b>	4	19	10.03 (2.58)	.29	.05
<b>IQ Block design</b>	4	19	11.83 (2.59)	.07	-.13
<b>MEMORY<sup>b</sup></b>					
<b>Verbal working memory</b>	-3.08	4.60	.002 (1.00)	.32	1.25
<b>Phonological short-term memory</b>	-3.14	3.36	.002 (1.00)	.07	.91
<b>LANGUAGE<sup>b</sup></b>					
<b>Naming task</b>	-4.23	2.21	-.036 (1.03)	-.54	.54
<b>Lexical comprehension</b>	-3.34	3.30	-.024 (.99)	-.20	.21
<b>Semantic fluency</b>	-3.00	3.40	-.041 (1.01)	.48	.30
<b>Syntactic comprehension</b>	-3.90	1.74	.002 (.96)	-.97	1.18
<b>ENVIRONMENTAL FACTORS</b>					
<b>Birth gestational age</b>	32	42	38.75 (2.18)	-1.08	1.07
<b>% &lt;37 gestational weeks (n)</b>	15 (98)				
<b>SES</b>	20	90	56.40 (19.03)	.08	-.80
<b>% Low SES<sup>c</sup> (n)</b>	16.3 (105)				
<b>% Medium SES<sup>c</sup> (n)</b>	43.2 (279)				
<b>% High SES<sup>c</sup> (n)</b>	40.6 (262)				
<b>HLE</b>	19	65	47.28 (7.50)	-.36	.01

<sup>a</sup> IQ Vocabulary and IQ block design are expressed in age-normed scores ( $M= 10$ ;  $SD= 3$ )

<sup>b</sup> Language measures were standardized on age-based general population ( $M= 0$ ;  $SD= 1$ ) and memory measures were age-standardized z-scores ( $M= 0$ ;  $SD= 1$ ) based on our sample mean **in each year level**; SES= Socioeconomic status; HLE= Home Literacy Environment;

<sup>c</sup> Low SES  $\leq 30$  points; 40 points  $\leq$  Medium SES  $\leq 60$  points; High SES  $> 60$  (Hollingshead, 1975)

Table 2

*Pearson correlations between memory, language and environmental factors (n= 646)*

	<b>IQ</b>	<b>IQ Block</b>	<b>pSTM</b>	<b>vWM</b>	<b>Naming</b>	<b>Semantic</b>	<b>Lexical</b>	<b>Syntactic</b>	<b>Birth</b>	<b>HLE</b>	<b>SES</b>
	<b>Vocabulary</b>	<b>Design</b>			<b>Task</b>	<b>Fluency</b>	<b>Comprehension</b>	<b>Comprehension</b>	<b>Gestational Age</b>		
<b>IQ Vocabulary</b>	1	.22**	.16**	.10**	.20**	.27**	.25**	.29**	.06	.10**	.20**
<b>IQ Block Design</b>		1	.11**	.14**	.26**	.13**	.25**	.19**	.02	.01	.09*
<b>pSTM</b>			1	.30**	.03	.12**	.11**	.10*	.03	.08	.12**
<b>vWM</b>				1	.15**	.13**	.08	.14**	.14**	.06	.08*
<b>Naming Task</b>					1	.29**	.26**	.28**	.01	.07	.07
<b>Semantic Fluency</b>						1	.26**	.20**	.05	.06	.17**
<b>Lexical Comprehension</b>							1	.23**	.02	.05	.12**
<b>Syntactic Comprehension</b>								1	.09*	.11**	.13**
<b>Birth Gestational Age</b>									1	.05	-.01
<b>HLE</b>										1	.18**
<b>SES</b>											1

*Note.* vWM= verbal working memory; pSTM= phonological short-term memory; SES= Socioeconomic status; HLE= Home Literacy Environment. \* $p < .05$ ; \*\* $p < .01$ .

Table 3

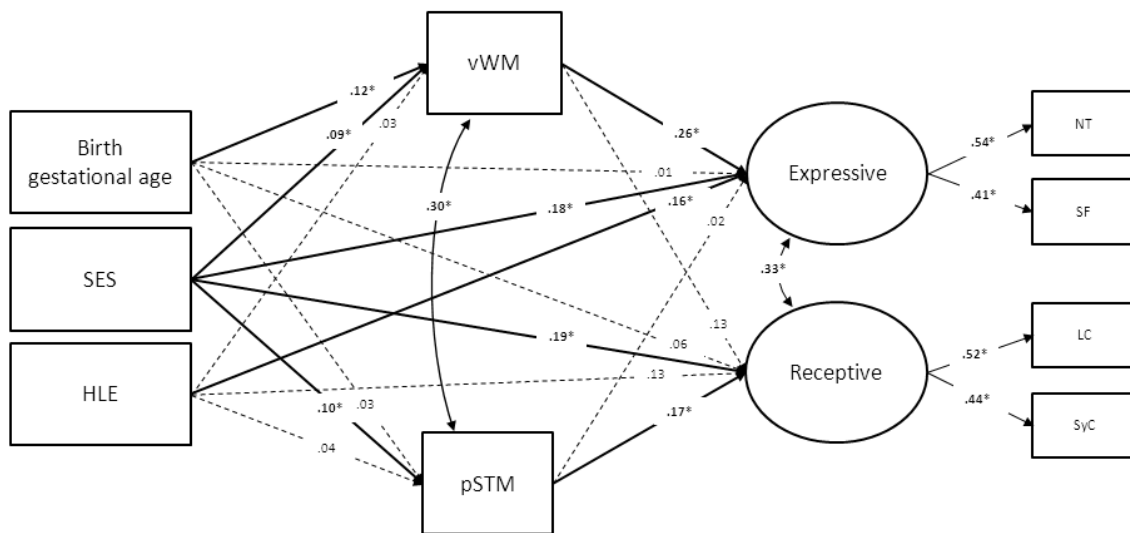
*Standardized indirect effects and 5000 bootstrapping confidence interval (CIs 95%)*

<i>Indirect effect</i>	<b>Estimate (SE)</b>	<b>Bootstrap [CIs 95%]</b>	<b>p-value</b>
<b>Birth gestational age → pSTM → EXPRESSIVE</b>	.001 (.004)	[-.008, .009]	.897
<b>SES → pSTM → EXPRESSIVE</b>	.002 (.009)	[-.016, .020]	.816
<b>HLE → pSTM → EXPRESSIVE</b>	.001 (.005)	[-.009, .010]	.877
<b>Birth gestational age → vWM → EXPRESSIVE</b>	<b>.031 (.014)</b>	<b>[.003, .058]</b>	<b>.030</b>
<b>SES → vWM → EXPRESSIVE</b>	.022 (.012)	[-.002, .046]	.086
<b>HLE → vWM → EXPRESSIVE</b>	.008 (.012)	[-.015, .031]	.479
<b>Birth gestational age → pSTM → RECEPTIVE</b>	.001 (.004)	[-.012, .021]	.587
<b>SES → pSTM → RECEPTIVE</b>	.018 (.010)	[-.003, .038]	.087
<b>HLE → pSTM → RECEPTIVE</b>	.006 (.008)	[-.010, .023]	.461
<b>Birth gestational age → vWM → RECEPTIVE</b>	.016 (.011)	[-.006, .037]	.146
<b>SES → vWM → RECEPTIVE</b>	.011 (.009)	[-.006, .029]	.202
<b>HLE → vWM → RECEPTIVE</b>	.004 (.007)	[-.010, .018]	.544

\*Significant mediation effect; Estimate= standardized coefficient; SE= Standard Error; pSTM= phonological short-term memory; vWM= verbal working memory; SES= Socioeconomic status; HLE= Home Literacy Environment.

Figure 1

*The tested mediation model*



*Note.* Chi-square= 24.68, df=11,  $p=.01$ ; Root mean square error of approximation (RMSEA)= .046, 90% CI= .021-.070; comparative fit-index (CIF)= .96; Standardized Root Mean Square Residuals (SRMR)= .025. Non-significant paths are indicated by a dotted line. pSTM= phonological short-term memory; vWM= verbal working memory; SES= socioeconomic status; HLE= Home Literacy Environment; NT= naming task; SF= semantic fluency; LC= lexical comprehension; SyC= syntactic comprehension; \* $p<.05$ .