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Inter-group and Inter-individual variability in working memory from childhood to emerging adulthood

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ABSTRACT

This report is a cross-sectional study aiming to establish the status of age inter-group and individual variability for Working Memory (WM) for the three WM components: Phonological loop (PL), Visuo-spatial Sketchpad (VSS) and Central executive (CE). The direct scores of the CE, the PL and the VSS were obtained in a sample of 258 subjects between 6 and 26 years. The obtained results indicate an increase of direct scores with age that was modeled by an age inverse function. The absolute age inter-group variability increased with age while the relative variability was constant across ages. The WM individual developmental variability showed that although a single principal component would explain the total variability, there was a closer relationship between the development of CE and PL with respect to VSS. The obtained results suggest that the range of WM relative competence is preserved along development which would favour the ecological adaptive value of WM across ages.

1. Introduction

1.1. Working memory: Definition and components

WM corresponds to a crucial executive function needed for subjects' cognitive operations, and is considered as one of the basic executive functions during development (Miyake et al., 2000). One of the most accepted definitions of WM is Postle´s (2006), in which "working memory is the retention of information in conscious perception, its manipulation and its use in guiding behavior, when that information is not present in the environment".

In 1974, Baddeley and Hitch described a WM model based on empirical results (Baddeley & Hitch, 1974; Baddeley, 2012) with a three-component structure: Two systems related to information storage, VSS and PL, and a CE. Pickering and Gathercole (2001) have developed the Working Memory Test Battery for children (WMTBC) that operationalizes the measure of these three components with a developmental approach. WMTBC is conceptually based on Baddeley and Hitch's (1974) Working Memory model.

The PL is responsible for the temporary maintenance of verbal and auditory information in the brain. The VSS is involved in the cognitive retention and processing of visual and spatial information for a limited time. The VSS and the PL are subordinated to the Central Executive (CE), since their functions are distributing the information received among the different subsystems and coordinating the cognitive processes carried out by them. It is also in charge of the attention and strategic aspects of cognitive processes (Baddeley, 2010; and is the link between subsystems and long-term memory (McCabe et al., 2010). According to Baddeley (2010), there is a fourth component in the WM model, called the episodic buffer, which corresponds to a system of limited and temporary storage capacity that can relate and integrate information from the other subsystems and long-term memory into a single episodic representation.

WM is related to the maintenance and manipulation of information and can be metaphorically visualized as a mental blackboard where the intended tasks are solved (Baddeley, 2012). It is characterized by a wide range of information content, either external or internal information, since these can range from elements of long-term memory, to newly acquired information, or even the results of operations that take place in WM. However, there are limitations in the processing of information by WM: restricted storage capacity, and limited duration of information maintenance (Cowan, 2010). These processing limitations are related to the interferences that competing stimuli easily produces in WM. The WM construct is related to that of fluid intelligence (Engle et al., 1999), and is of particular importance in the development of curricular activities. According to Cowan (2014), WM is a crucial part of cognitive processing and allows to carry out more complex and necessary functions of daily life, such as linguistic comprehension, reading, reasoning, and

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others cognitive functions. It is also key in the interaction between the information received and long-term memory by retrieving stored information that may be relevant, reinforcing its role in the development of curricular activities (Cowan, 2014).

1.2. Interdependence of developmental individual differences of the Working Memory components (IDWM)

WM development has been studied through experimental tasks, but also by means of psychometric batteries, such as the WMTBC which operationalizes the Hitch and Baddeley WM model (Gathercole and Pickering, 2000). As the present report deals with the maturation of the WM component model, we would comment only aspects related to the WM components development. (Hitch et al., 1988). The structure in the three components is clearly attained at 7 years of age in terms of organization and strategies (Gathercole and Hitch, 1993). The format of coding information changes with age, with young children using visual information, and adding verbal recoding of information after 8 years old by using the PL (Hitch et al., 1988). The verbal formatting, which would permit the use of the verbally based rehearsal mechanism, would be part of the increase in visuospatial WM performance with age, although other mechanisms not well understood would also be related to the increase of VSS capacity with age. An additional factor for increased efficacy would be in the increase of the rehearsal rate that would liberate WM space facilitating the capacity increase of verbal information (Hulme et al., 1984).

Concerning the structural development of WM, the PL and VSS develop independently in the 5-8 years old period (Pickering et al., 1998). The independence of the VSS and PL was confirmed in preadolescents (11–14 years; Jarvis and Gathercole (2003). The PL and CE showed a moderate association in 6- and 7-year-old children (Gathercole and Pickering, 2000). In a confirmatory analysis and by using the WMTBC in children and adolescents (6 to 15 years) the independence of the three WM components was demonstrated (Gathercole et al., 2004; Barriga-Paulino et al., 2016). Despite the statistical independence between the three component a closer association between CE and PL than between CE and VSS was found. The WM reaches a plateau at 15 years, with CE attaining the highest performance later than the slave systems. The increased efficiency of WM operations with age would permit the release of space facilitating the increase of capacity which is observed in WM (Case, 1992). Interestingly, the WM individual variability is addressed in scientific literature in relation to individual variability of other cognitive functions such as processing speed (Mella et al., 2015) fluid intelligence (Fry and Hale, 2000), but only in a limited manner by itself (Gathercole et al., 2004).

1.3. Individual differences variability between age groups (age inter-group variability)

Variability refers to the differences between the factors measured at different measurement points. In the present report the main objective is to observe if the magnitude of individual variability of WM direct scores differs between age groups during children and adolescent development (age Inter-group WM variability). Although age inter-group variability is described in WM psychometric tests (Pickering and Gathercole, 2001; Rosselli-Cock et al., 2004), however no effort is made in order to understand if the intergroup absolute variability (measured as standard deviation of direct scores), and relative variability (measured as coefficient of variation of direct scores) changes in the different age groups. As far as we know this aspect has not been studied in the WM literature. In particular, and concerning more complex measures of WM as those included in the Baddeley and Hitch model the magnitude of individual differences between difference age groups has not been studied. This aspect is of societal importance given that subjects of a given age group have to share the same ecological niches and be under the same social pressure, as for instance the same classroom and curricula demands. Therefore, the knowledge of the expected variability in individual differences for each age group should be a primary concern for educators.

1.4. Objectives and hypotheses

The aims of the present report are (i) to determine if inter-group individual differences variability of direct scores of WMTBC differs in different age groups, and (ii) if the there is a relationship between the development of the different components of the WMTBC Baddeley and Hitch model. With respect to the inter-group differences variability between age groups there are no specific hypotheses. For the second objective, a higher relationship between the direct scores of CE with PL, than with VSS is expected following previous results (Gathercole et al., 2004). The latter objective corresponds to computing the individual variability interdependence between the direct scores of WMTBC across development.

2. Material and methods

2.1. Sample

The database is made up of 258 subjects, approximately distributed equally by gender: 134 males (M = 14.49, St = 6.25; range = 6–26). and 124 females (M = 14.35, St = 5.88; range = 6–26). A subsample of 167 (Rodríguez-Martínez et al., 2013) and 108 subjects (Barriga-Paulino et al., 2016) were previously used for other complementary purposes. For the analysis of the inter-group WM variability subjects between 6 and 18 years were organized in groups of one year. Due to a reduced number of participants from 18 years of age to 26 years, subjects were organized in groups with a range of 2 years instead of 1 year, in order to match the groups size with the number of participants per group under 18 years of age. Table 1 shows the distribution of subjects grouped by years. The sample was recruited from the local community and tested in a lab located at the Psychology school.

The selected subjects did not report to have been diagnosed of any neurological, psychological or psychiatric impairment and they were not taking any psychotropic pharmaceutical compound. Additionally, all participants in school and high school age were enrolled in the grade corresponding to their biological age. The participants were extracted from a middle-class socioeconomic background.

Experiments were conducted with the informed and written consent of each participant (parents/tutors in the case of the children and adolescents) following the Helsinki protocol. The study was approved by the Bioethical Committee of the Junta de Andalucía (https://www.juntadeandalucia.es/salud/portaldeetica/).

2.2. Testing

2.2.1. Working Memory Test Battery for Children (WMTBC)

The WMTBC by Pickering and Gathercole (2001), which is based in the WM model of Baddeley (2012) was used. The researcher obtained the informed consent signed by the subjects participating in the study. The test measures three WM components: PL, VSS and CE. This test is made up of 9 subtests that were applied in the following order: (1) Digit Recall, (2) Word List Matching, (3) Word List Recall, (4) Nonword List Recall, (5) Block Recall, (6) Mazes Memory, (7) Listening Recall, (8) Counting Recall, and (9) Backward Digit Recall. The subtests 1, 2, 3 and 4 measure the phonological loop, subtests 5 and 6 measure the visuospatial sketchpad, and subtests 7, 8 and 9 measure the central executive.

The original battery was in English, but the battery used in our laboratory was translated into Spanish (Rodríguez-Martínez et al., 2013). The following subtest were applied as in the original battery, just translating from English when needed: The Digit Recall, Backward digit recall, Block Recall, Counting Recall, Mazes memory. However, for the

Table 1
Subjects age and gender.

Age	Number of subjects	Gender ratio
6	18	Male: 9 Female: 9
7	14	Male: 9 Female: 5
8	19	Male: 8 Female: 11
9	16	Male: 8 Female: 8
10	18	Male: 11 Female: 7
11	14	Male: 7 Female: 7
12	16	Male: 9 Female: 7
13	16	Male: 8 Female: 8
14	15	Male: 7 Female: 8
15	11	Male: 6 Female: 5
16	12	Male: 7 Female: 5
17	12	Male: 5 Female: 7
18	17	Male: 8 Female: 9
20	16	Male: 8 Female: 8
22	16	Male: 8 Female: 8
24	16	Male: 8 Female: 8
26+	12	Male: 8 Female: 4
	258	

following subtests some specific criteria were needed for the Spanish translation:

- For the Word List Matching and Word List Recall subtests, disyllabic words obtained from a word frequency list used by children were employed, with similar lengths to original words and high frequency of use, in order to facilitate the testing of young children (Justicia, 1995).
- For the Nonword List Recall subtest, we used the same words as on the previous subtests. To convert words into nonwords, we changed the vowel order within words and the order of the syllabi that composed each word.
- For the Listening Recall subtest, we simply translated the original sentences from English to Spanish, in order to maintain the reliability of the task. The Direct scores obtained from the WMTBC were used for statistical analysis.

The stimuli used in the visuo-spatial tests of the WMTB-C are selected on the basis of being very difficult to recodify verbally because they do not correspond to namable family objects. On tasks involving such materials, older children and adults should use nonverbal forms of the short-term memory store.

2.3. Possible gender differences

Gender was evaluated as a possible significant variable in the WM direct scores obtained using a T-test for independent samples. There were no statistically significant differences in the PL and VSS directs scores, however, in the direct CE scores, a significant difference at the limit of Type I error significance (p = .049) was observed. The limited gender differences precluded to separate by gender for the sake of simplicity.

2.4. Statistical analysis

The first aspect analyzed was to determine which type of regression model best fits the improvement with age of the direct WM scores: The regression of each of the direct scores obtained from WMTBC vs. age in days was computed using linear, logarithmic, inverse, quadratic, cubic, potential, growth and exponential models as implemented in SPSS Statistics 26. As the inverse regression was selected to model the functional relationship between direct scores and age (see below) (direct scores = b0 + (b1/age), the residuals between the recorded direct scores and the predicted values were obtained for subsequent analysis (age residuals from now).

For the analysis of age inter-group WM direct scores variability, the following strategies were used:

-Absolute individual differences variability of the different age groups:

For this objective, the standard deviation (SD) of the direct scores of CE, PL and VSS in each age group was computed and then a linear regression of the latter value vs. the mean age of the age group was computed (see Figs. 2 A–C). As each standard deviation WM component regression presented an age group that could be classified as an outlier (-2.8<z<2.8), which corresponds to $p = 0.005$ bilateral under the normal probability curve, the regression of standard deviations of the direct scores in each age group vs. group age was repeated again eliminating the outlier in each WM component regression (see Figs. 2 D-F).

-Relative inter-individual variability in the different age groups:

To reduce the effect of the absolute value of direct scores in the computation of age inter-group variability through standard deviation, which is affected by the numbers magnitude, two different procedures were applied: The coefficient of variation of direct scores in each age group (CV), and a method based on the residuals of the direct scores vs. age. For the former, the CV (CV=SD/mean) obtained in each age group and regressed against group age. The method of residuals pretends to obtain a measure of individual variability discounting the effect of maturation by obtaining the predicted direct score from the age, and subtracting the predicted values from the empirical direct scores. The age residuals were obtained from the regression between the direct scores of WMTBC vs. age using the inverse model as indicated previously in the results section (see Table 2). To determine the possible relationship of the age inter-group relative variability with age based on the residual direct scores, the linear regression of the standard deviation of the age residuals scores in each age group vs. the age group was computed.

-Individual variability interdependence between the direct scores of WMTBC across development:

Two different strategies were used to observe if a given subject which is advanced or protracted in a given WM direct score with respect to the expected value for his/her age is also advanced or protracted in another measurement. The methods would be based in Principal Component analysis (PCA) and in the linear regressions of the age residuals. The use of age residuals in both methods, obtained using an age inverse model, permitted to focus the analysis on the individual variability over or under the predicted values for the subject´s age, reducing the impact of the age factor that would absorb most of the data variability. PCA permits to obtain a reduced set of latent variables explaining the variance of the empirical variables (Gorsuch, 1983). The Varimax orthogonal rotation would be applied to the variables introduced in the PCA. The Varimax rotation, while keeping orthogonality between components facilitates results interpretation given that it rotates the axes to explain the higher proportion of variability in a reduced number of components. The criterion followed to decide which components are extracted was the Kayser criterion (eigenvalues > 1). In order to interpret the meaning of the extracted components, the values of the loading components were taking into account. The loading component represents the correlation between the scores obtained for each subject in each PCA component vs. the empirical scores of a given variable. Before doing the PCA and the regressions the residuals having a z-value higher than 2.8 or lower than -2.8 were removed (1 case for VSS, 1 case for CE).

Table 2
Summary of model and parameter estimates in Working Memory direct scores vs age regressions. Dependent variables were Phonological Loop, Visuo-spatial Sketchpad and Central Executive direct scores. The independent variable was Age masured in days.

Model summary and parameter estimates Phonological Loop									
Equation	Model summary					Parameter estimates			
	R^2	F	DF1	DF2	Sig.	Constant	b1	b2	b3
Linear	,16	50,16	1	255	$p < 0.001$	101,57	,004		
Logarithmic	,20	63,74	1	255	$p < 0.001$	-56,32	20,8		
Inverse	,22	72,39	1	255	$p < 0.001$	142,67	-98585,3		
Quadratic	,22	36,77	2	254	$p < 0.001$	70,82	,016	-1,018E-6	
Cubic	,22	24,77	3	253	$p < 0.001$	54,96	,025	-2,762E-6	9,589E-11
Potencial	,21	68,34	1	255	$p < 0.001$	26,59	,177		
Growth	,17	52,97	1	255	$p < 0.001$	4,61	3,031E-5		
Exponential	,17	52,97	1	255	$p < 0.001$	101,4	3,031E-5		
Model summary and parameter estimates Visuospatial Sketchpad									
Equation	Model summary					Parameter estimates			
	R^2	F	DF1	DF2	Sig.	Constant	b1	b2	b3
Linear	,21	71,02	1	255	$p < 0.001$	41,53	,002		
Logarithmic	,30	110,00	1	255	$p < 0.001$	-56,00	12,77		
Inverse	,37	151,00	1	255	$p < 0.001$	66,72	-63847,17		
Quadratic	,41	88,88	2	254	$p < 0.001$	13,96	,013	-9,130E-7	
Cubic	,42	63,07	3	253	$p < 0.001$	-5,87	,025	-3,094E-6	1,200E-10
Potencial	,31	116,61	1	255	$p < 0.001$	5,385	,266		
Growth	,22	72,71	1	255	$p < 0.001$	3,716	4,255E-5		
Exponential	,22	72,71	1	255	$p < 0.001$	41,098	4,255E-5		
Model summary and parameter estimates Central Executive									
Equation	Model summary					Parameter estimates			
	R^2	F	DF1	DF2	Sig.	Constant	b1	b2	b3
Linear	,37	151,96	1	255	$p < 0.001$	46,86	,004		
Logarithmic	,43	199,25	1	255	$p < 0.001$	-146,13	25,52		
Inverse	,47	226,90	1	255	$p < 0.001$	97,25	-119000,72		
Quadratic	,47	112,68	2	254	$p < 0.001$	14,61	,017	-1,068E-6	
Cubic	,47	76,08	3	253	$p < 0.001$	-2,03	,027	-2,898E-6	1,006E-10
Potencial	,45	214,82	1	255	$p < 0.001$	2,57	,386		
Growth	,38	156,10	1	255	$p < 0.001$	3,87	6,704E-5		
Exponential	,38	156,10	1	255	$p < 0.001$	48,14	6,704E-5		

In order to visualize more clearly the possible relationship of individual variability between the different WM direct scores, after discounting the effect of age, the age residuals of the direct scores vs. age were linearly regressed between them. With this method it would be possible to observe if one subject which is advanced or protracted in development in a certain measure is also delayed or protracted with respect to another.

3. Results

To evaluate the increase in direct scores with age and validate the most appropriate regression model to explain the WM direct scores of WMTBC components, the WM scores were regressed vs. the age with different models: linear, logarithmic, inverse, quadratic, cubic, potential, growth and exponential. Most models were significant for WMTBC direct scores (Table 2). In order to choose the same model for fitting all the variables the goodness of fit (as estimated by R^2) in the different variables being high and the simplicity, the need for estimating less parameters was used. The inverse model fulfilled both criteria for the regressed variables (Table 2). The Fig. 1 shows the direct scores of WMTBC vs. age using an inverse model fitting.

To study the absolute variability of the direct scores with respect to the age groups, the SD of direct scores of each age group were linearly regressed vs. the age group (Fig. 1A-C). Only the phonological loop vs. age was statistically significant when regressed vs. age. However, one outlier ($-2.8<z<2.8$, $p = 0.005$ bilateral) was present in each of the age groups SD used for the regressions. Figs 1D-E, shows the regression of the age groups SD of the direct scores once the outliers were removed, showing a statistically significant increase of WM standard deviation with age for the three WM components.

Table 3
Loading components and explained variance of the components extracted after applying PCA to the age residuals of the WMTBC (258 subjects).

Component Matrix[a]	Component 1
Phonological loop residual direct scores	,842
Visuospatial Sketchpad residual direct scores	,497
Central Executive residual direct scores	,882

Explained variance 57.84%

With respect to the analysis of WM age inter-group relative variability obtained by linearly regressing the CV vs. age group for each WM model component direct scores were not significant. Similarly, the age residuals SD of WMTBC direct scores of each age group when regressed vs. group age were not statistically significant.

Individual variability interdependence between the direct scores of WMTBC across development:

One single component was extracted from the PCA of the age residuals direct scores obtained from WMTBC. The loading factors and the explained variance appears in Table 3. indicating a higher relationship of

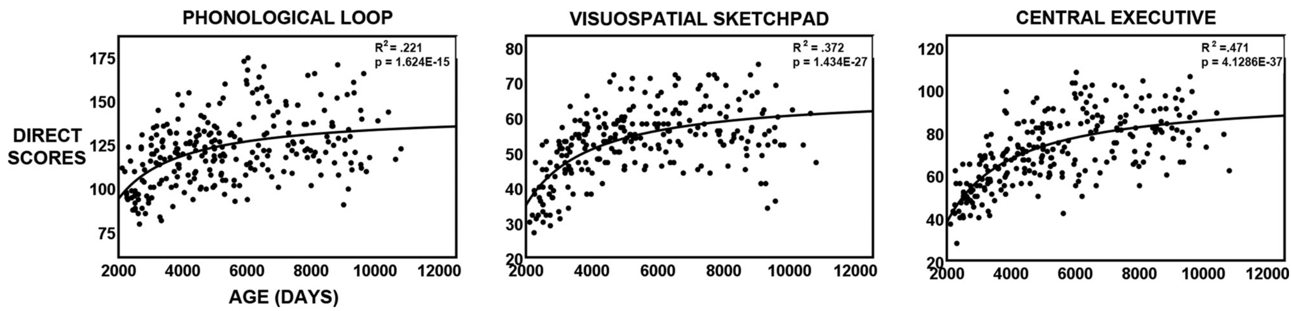

Fig. 1. Inverse regression of Working Memory components direct scores (Phonological loop, Visuospatial Sketchpad and Central Executive Direct Scores)vs. Age was measured in days. The age inverse model confirmed previous results obtained with a subsample of these data (Rodríguez-Martínez et al., 2013).

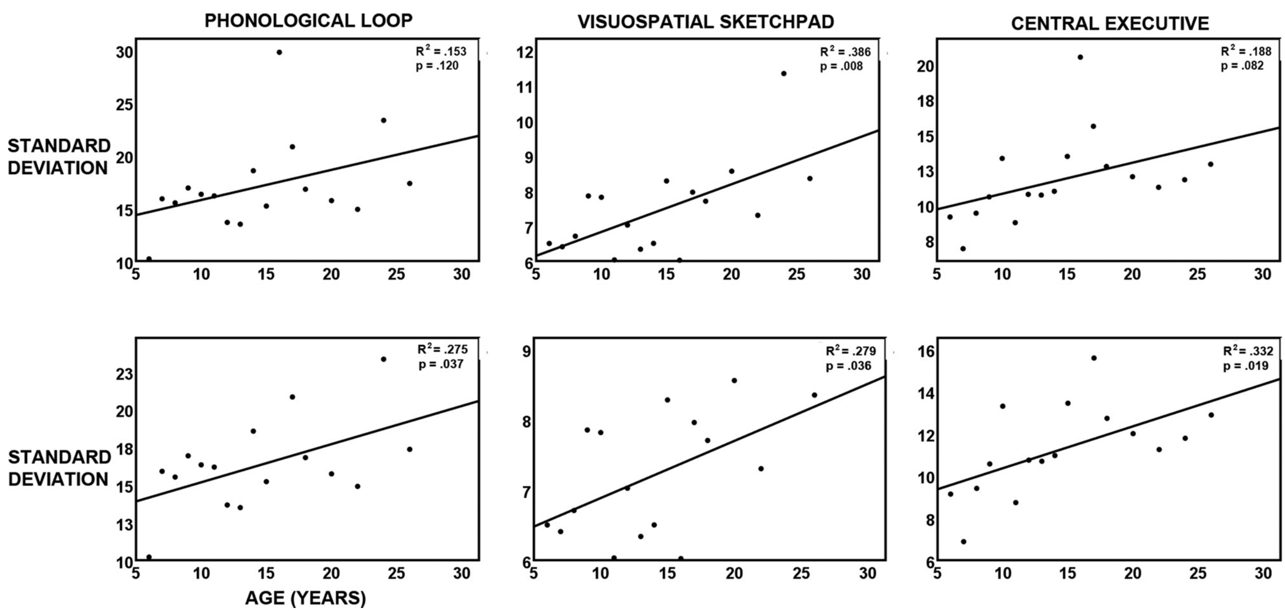

Fig. 2. Linear regressions of Phonological loop, Visuospatial Agenda and Central Executive Standar deviations vs. the age group age measured in years. No-excluding (above) and excluding (below) the Standard deviation outlier values.

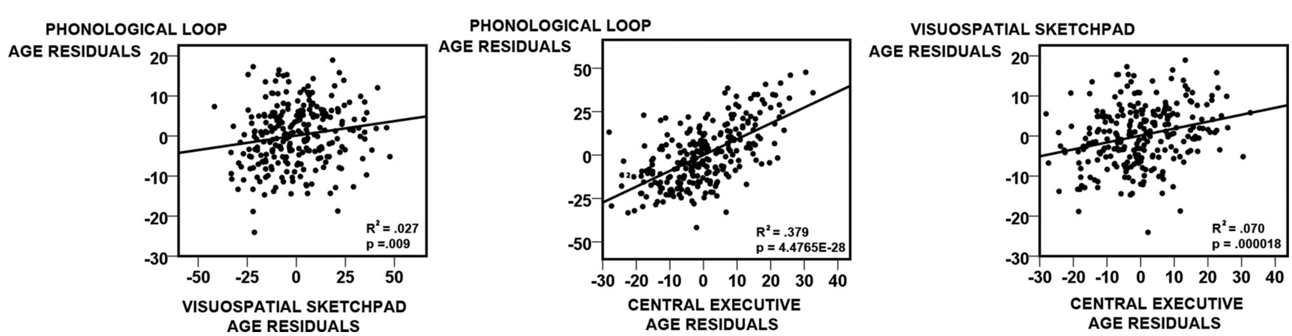

Fig. 3. Linear regression of the age residual scores of the Working Memory components.

the extracted component with CE and PL than with VSS. Fig. 3 shows the regressions of the age residuals of the WM components. All the WM age residuals regressions were significant (Fig. 3A, 3B and 3C). The strongest relationship of the PL with the CE age residuals (Fig, 3B) was evident, when compared with the regressions between the PL and VSS age residuals (Fig. 3A) and VSS and CE age residuals (Fig. 3C).

4. Discussion

The present study had two main objectives. The first objective tried to study whether the variability of the direct scores of the WM differs in the different age groups and the second one, to study a possible relationship of interdependence between the development of WM components. For the first objective the main findings were (i) the absolute variability of direct WM scores increases with the age of the groups and (ii) the relative variability did not increase with the group age. To accomplish the latter objective, it was needed to demonstrate that the increase of WM direct scores with age was modelled by an inverse relationship, whit higher increase in WM capacities in youngest children with respect to adolescents, as it was previously demonstrated with a subsample of present data (Rodríguez-Martínez et al. 2013). For the second objective the developmental individual variability showed a strong relationship between CE with PL, while the relationship between CE and VSS, and PL and VSS development was lower.

The present study concludes that there is an increase in the intergroup absolute variability of WM with age, probably due to an indirect effect of magnitude increase of direct scores with age, while there is a maintenance of the relative variability, once the effects of the numerical magnitude of direct scores are eliminated. The constancy of relative variability across ages would guarantee the same effective variability in each age group with the same level of interindividual competence in the different age groups. An economic metaphor would illustrate the importance of the maintenance of the relative age inter-group variability in WM. Suppose that children play economic games with cents, while adults invest in dollars: the magnitude is very different, but if the relative variability of economic capacity is maintained in children with respect to adults it would imply a high ecological validity of children play for future adult economic scenarios, something that would not be preserved if the relative inter-group economic capacity were not preserved in the different age groups during play and investment. The stable relative variability of WM across ages implies a similar variability in WM competence that would replicate in the ecological niche of children the ecological situation of adults with respect to WM capacity. The regulatory mechanism for this variability (evolutionary, social, cultural, etc.) would require further research. Although the absolute variability in age groups is commonly reported in WM psychometrical tests (Pickering and Gathercole, 2001; Rosselli-Cock et al., 2004), no further effort is being devoted for the exploration of the possible differences in absolute and relative variability between age groups. However, in computerized tasks the age intergroup variability shows a decrease in absolute variability of the number of errors with the increase of age in a variety of different types of computerized tasks (Rojas-Benjumea at al., 2013; Luna et al. 2004; Mondloch et al., 2003), although neither the absolute nor the relative age intergroup variability are explicitly studied, except for the Rojas-Benjumea study (2013) which showed a significant increase of absolute errors variability in children with respect to adolescents. The possible differences in absolute and relative variability performance variability across ages in psychometric and computerized tasks should be further studied given the already indicated importance to define the range of population processing capacities of subjects at different ages. The range of cognitive processing capacities is important for social niches of particular importance such as the classroom.

Concerning the IDWM which proposes the analysis of the interdependence of the development of the WM components, the PCA replicates previous results from Gathercole et al. (2004), showing that CE and PL present a closer relationship than CE with VSS and PL with VSS. This conclusion is not only supported by the presence of one PCA component which links closely CE with PL, but also by the age residuals regressions, that clearly showed that a given subject which is developmentally advanced or protracted with respect to CE is also delayed or protracted with respect to PL. The relative independence of the VSS and PL development confirms previous results obtained in children and preadolescents (Gathercole and Pickering 2000, Jarvis and Gathercole 2003; Gathercole et al., 2004). However, the significant developmental relationship between all the WM components suggests, as indicated by the single PCA obtained component, that the developmental independence of VSS is only relative and that there is a common factor underlying the WM components development, including the VSS which was obtained from subtests in which a careful design is followed to avoid a verbal recoding that naturally arises in children (Gathercole & Hitch 1993, Hitch and Halliday 1983; Hitch, Halliday, Schaafstal and Schraagen, 1988).

5. Conclusions

As conclusions (i) The WM capacity increase with age can be modelled by an inverse function, (ii) the preservation of a relative similar range of WM competence across age is obtained, suggesting that the higher order cognitive strategies developed by subjects with different levels of WM capacity would be adaptive as age progresses, and (iii) a closer developmental association exists between CE and PL with respect to VSS.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Credit roles of authors

Raquel Muñoz-Pradas: Conceptualization, Data curation; Formal analysis; Methodology; Project administration; Roles/Writing - original draft; Writing - review & editing.

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Elena I. Rodriguez-Martínez: Conceptualization; Data curation; Investigation; Methodology.

Carlos M. Gómez: Conceptualization, Funding acquisition; Methodology; Project administration; Supervision; Visualization; Roles/Writing - original draft; Writing - review & Editing.

Data and code availability

Due to the sensitive nature of the questions asked in this study, survey respondents were assured raw data would remain confidential and would not be shared.

The research protocols used in this research were approved by the ethics committee of the University of Seville.

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