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Order of maturation of the components of the working memory from childhood to emerging adulthood

Raquel Muñoz-Pradas, Miriam Díaz-Palacios, Elena I. Rodriguez-Martínez, Carlos M. Gómez*

Human Psychobiology Lab, Experimental Psychology Department, Psychology School, University of Sevilla, Spain

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ABSTRACT

The objective of this paper was to analyze the maturation order of WM components Phonological loop (PL), Visuo-spatial Sketchpad (VSS) and Central executive (CE), from childhood to emerging adulthood in subjects aged between 6 and 29 years~~,~~ by means of Bonferroni comparisons between the direct scores of the different age groups. The WM direct scores were obtained with the Working Memory Test Battery for Children (WMTBC). Linear regressions between age and Z-scores of the direct scores of the three components of the WM were carried out. The results indicate that the different components of WM are linearly related to age, from 6 to 15 years old, replicating previously obtained results. ANOVA and Bonferroni-type comparisons show that there is a different order of maturation among the components that make up the WM, with the central executive being the component that matures later. A peculiar result was observed in the 16–17-year group for PL and CE. This group presents a significant difference with all the groups of lower age.

1. Introduction

1.1. *Working memory: definition, components and models*

Working memory (WM) is a psychological process of psychobiological and neurophysiological origin, which is involved in the temporary storage and manipulation of information to execute complex cognitive functions, including language, understanding, learning and reasoning (Baddeley, 1992). WM also allows keeping active the information and operations necessary to solve a task. WM is a system that has the ability to store information in a short period of time (for seconds) and process the stored information (Baddeley, 1992). Memory is especially important in the field of curricular activities and in the cognitive development of the child, fulfilling such important functions as assimilating different types of information, and in turn, interacting with long-term memory to rescue relevant and semantically related information On the other hand, it is also capable of facilitating the consolidation of the contents of the working memory in long-term memory (LTM) and allowing a behavior directed towards objectives (Baddeley, 2012).

Several models have proliferated to explain WM and its development, for instance those of Pasqual-Leone (1994) and Cowan (1995) (for a review on developmental issues of these models see: Gómez et al., 2018 and 2021).

1.2. *Development of WM according to the Baddeley & Hitch model*

Baddeley and Hitch (1974) proposed one of the most relevant models to explain the functioning and structure of WM. This model is empirically based through experiments in which the performance of each component can be independently interfered by concurrent tasks (Baddeley, 2012). The WM is composed by a central executive (CE), which is in charge of coordinating the slave components, the visuo-spatial sketchpad (VSS) and the phonological loop (PL), and allows interaction with LTM. CE is important in novel situations such as problem solving, planning, selection of strategies (Baddeley, 2012) and complex situations such as multitasking. The CE component participates in tasks that require immediate processing, high-level attentional control and/or coordination of attention.

On the other hand, PL and VSS are specialized systems for the manipulation and retention of material in particular information domains. The PL component is responsible for storing temporarily and processing verbal information, and the VSS is responsible for storing and processing visual and spatial information (Logie et al., 1990).

More recently a fourth component called episodic information buffer memory has been added (Baddeley, 2000). This new system is in charge of simultaneously storing phonological and visual information of the slave systems, and it is capable of integrating information from the LTM (Baddeley, 2000).

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* Corresponding author at: Departamento de Psicología Experimental, c/Camilo José Cela s/n, Sevilla 41018, Spain.
E-mail addresses: raqmumpra@alum.us.es (R. Muñoz-Pradas), elisroma@us.es (E.I. Rodriguez-Martínez), cgomez@us.es (C.M. Gómez).

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The WM maturation depends on several aspects, such as the type of information that is stored, the encoding, the retention of the information, and the changes related to the maturation of executive functions that mainly involve a specific area of the brain, the prefrontal cortex (Klingberg et al., 2006). WM development would be related to the maturation of WM processing and WM structure and with the increased performance as age progresses. The Working Memory Test Battery for Children (WMTBC; Gathercole and Pickering, 2001) which operationalizes the Baddeley and Hitch Component Model in a population between 6 and 14 years old has been widely used for this purpose. It appears that from 6 years of age, a child's WM presents a structure similar to adults (Gathercole et al., 2004), and the differentiation between the two slave systems is already in place at five years (Pickering et al., 1998). They also found that the change from a visual information coding strategy based solely on visual characteristics of objects to a strategy in which visual information can be supported by verbal strategies occurs around 7–8 years (Gathercole et al., 2004). Although more recent data suggests that the three componential model with a common resource processor and two short-term slave domain-specific systems is already in place at 4 years old (Alloway et al., 2006). The improvement with age of verbal information rehearsal would allow to stabilize the working memory contents.

WM participates in complex cognitive skills and school-related measures, for example, reading comprehension (Carretti et al., 2009), mathematical performance (Passolunghi and Costa, 2019; Raghubar et al., 2010), academic achievement and intelligence (Tourva et al., 2016). Therefore, the understanding of the order of maturation of the different WM components would be important to understand the maturation of these high-level cognitive functions.

Therefore, the progress of WM depends on several aspects such as "the specific information processing of each modality, the encoding and retention in memory, the increase in capacity and the changes related to the maturation of cognitive functions that mainly involve to the prefrontal cortex" (Logie and Pearson, 1997; Nelson, 1995, 2000).

1.3. *Order of maturation of WM components*

Gathercole et al. (2004) suggested that there are no differences in maturation order of the WM components. They showed that there is a linear growth of the Z-scores of the WM tests included in the WMTBC in subjects between 4 and 14 years, stabilizing at 14 and 15 years of age, except for the visual pattern subtest test in which they found a performance stability at 11 years. In this study no ages higher than 15 years were explored. Alloway et al. (2006), have shown that in verbal short-term memory tasks performance leveled off at 10–11 years, while, visuo-spatial short-term memory, visuo-spatial and verbal working memory present a linear increase up to 11 years. However, in the latter study 11 years was the oldest tested group. Therefore, there is not a systematic study that would include children, adolescents and young adults to test maturation order of the WM components.

1.4. *Objectives and hypotheses*

The aims of this report are (i) to replicate the linear relationship between the direct scores, expressed in standardized scores, of the WM components with age, as carried out by Gathercole et al. (2004), and (ii) to analyze the maturation order of WM components (VSS, PL and CE) that make up the multicomponent model of WM, by means of Bonferroni comparisons between the direct scores of the different age groups. Regarding the hypothesis of this research, there could be a different maturation order for the systems that make up the multicomponent model of the WM. Possibly, the CE would be the last to mature due to the dependence on the prefrontal cortex maturation.

Table 1
Age and gender of the different age groups.

Age	(n)	Gender
6–7	32	Male: 18 Female: 14
8–9	35	Male: 16 Female: 19
10–11	32	Male: 18 Female: 14
12–13	32	Male: 17 Female: 15
14–15	26	Male: 13 Female: 13
16–17	24	Male: 12 Female: 12
18–19	17	Male: 8 Female: 7
20–21	16	Male: 8 Female: 8
22–29	44	Male: 24 Female: 20

2. Material and methods

2.1. *Sample*

The sample has been chosen in present form for two reasons; (i) the researchers wanted to study the development and maturation order of WM during this age period, and (ii) gender parity The sample of subjects for this study was made up of a total of 258 participants with ages between 6 and 29 years, 134 belonging to the male gender (52%, $M = 14.49$, DT = 6.249) and 124 to the female gender (48%, $M = 14.35$, DT = 5.885). They were divided into groups using the age criterion in years, forming two-year groups from 6 to 17 years old. Subjects in the age range 18–21 and 22–29 formed independent age groups. The group organization in different age ranges was done in order to approximately equate the number of subjects in each age group (see Table 1).

No diagnosed neurological, psychiatric or psychological disease was informed in any of the subjects. No subject was on pharmaceutical treatment. The socioeconomic level of the subjects was middle class and all the participants were in the school grade corresponding to their biological age. 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. *Working memory test battery for children (WMTBC)*

The subjects were tested with the Working Memory Test Battery for Children (WMTBc). This battery is composed of a total of 9 subtests, combined in a specific order to be able to measure through direct scores the three components that make up the WM (phonological loop, visuo-spatial sketchpad and central executive). The order of administration is as follows: (1) Digit Retrieval, (2) Word List Match, (3) Word List Retrieval, (4) Wordless List Retrieval, (5) Block Retrieval, (6) Mazes Memory, (7) Listening Recall, (8) Counting Recall, and (9) Digit Recall Backward. The combination of these subtests provides information regarding the different components: Phonological loop direct scores are obtained from tests 1, 2, 3 and 4, visuo-spatial sketchpad direct scores from 5 to 6 measure the second, and 7, 8 and 9 permitted to obtain the central executive direct scores. The battery used had to be adapted from English to Spanish, following a series of criteria such as:

- For the Word List Agreement and Word List Reminder sub-items, disyllabic words collected from a list of frequency of words used by children were used, with certain similar criteria such as the length

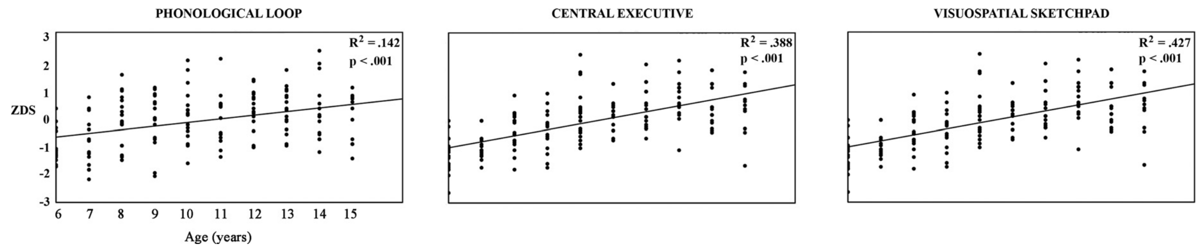

Fig. 1. Linear regressions of Phonological loop, Visuo-spatial Sketchpad and Central Executive Z-scores (ZDS) vs. the age group measured in years up to 15 years. Quitar 16.

Linear regressions of Phonological loop, Visuo-spatial Sketchpad and Central Executive Z-scores (ZDS) vs. the age group measured in years up to 15 years.

between the original words and high frequency of use, with in order to facilitate the completion of the test to younger age groups (Justicia, 1995).

- For the subtest of Retrieval of the list of non-words, the same words have been used as in the previous tests. To transform words into non-words, we changed the order of the vowels within the words and the order of the syllabi that made up each word

2.3. *Statistical analysis*

All the statistical analysis were computed with IBM SPSS Statistics 26.

- *WM components Z-scores linear regression with respect to age measured in years.*

A replica of the Gathercole et al. (2004) analysis was carried out, with the aim of studying the increase of Z-scores WM components with age. In order to replicate this analysis, only subjects with ages 15 or lower were selected. The Z-scores of the direct scores of the WM components obtained from the WMTBC were linearly regressed with the age group.

- *Order of maturation of WM components.*

To carry out the study on the order of maturation of the WM components with respect to age, univariate linear ANOVAS with the factors age groups and gender were computed with the direct scores of the PL, VSS and CE as dependent variables. Greenhouse-Geisser correction for sphericity was applied when needed. Bonferroni post-hoc were computed for the age group significant results. The post-hoc would permit to establish possible differences in the order of maturation of the three WM components.

3. Results

Linear regressions of the Z-scores of the three WM components with respect to age (up to 15 years old) were computed. All the regressions were significant (p <0.001) (see Fig. 1). Fig. 1 clearly shows a linear increase of direct scores with age for PL, VSS and CEE across these age groups.

To study the WM components, order of maturation a two-factor ANOVA was carried out to determine whether the variables gender and age were significant. The results show that the age variable measured in years were significant for the three components of WM: PL (F [7241] = 12.87, p<0.001. η^2=0.272 and observed power=1.000.; VSS (F [7241] = 27,583, p<0.001 η^2=0.445 and observed power=1.000; CE (F [7241] = 34,267, p<0.001), η^2=0.499 and observed power=1.000.

The Fig. 2 displays the increase of WM performance with age for the PL, VSS and CE components during childhood and adolescence, and the stabilization of direct scores values during early adulthood, in both: male and females. Bonferroni post-hocs were computed to show the significant differences between the age groups (see Table 2), which could provide information on the maturation order of the three WM components. The CE component presents the longest period to mature, showing statistically significant differences between the older groups up to the ages of 14–15 years, which implies that the complete maturation of this component does not end until the adolescent period (see Fig. 2 and Table 2). The direct scores of the VSS show statistically significant differences between the oldest groups and the 10–11-year group, but not with older groups than 10–11 years. The PL direct scores reached its peak of maturity at the age of 8–9 years because this age group was the most aged groups showing statistically significant differences with the older groups.

A peculiar result was observed in the 16–17-year group, which presents a significant difference with all the groups of lower age (see Fig. 2 and Table 2). These results represent that the verbal memory capacity is increased in the age of 16–17 years, with extremely high scores in this group. In the CE the 16–17-year-old group also showed a significant direct score increase, similarly to PL.

The gender factor was significant in VSS (F [1, 241] = 3.894, p <0.05; η^2=0.016 and observed power=0.5), and CE (F [1, 241] = 8.086, p <0.005, η^2=0.032 and observed power=0.8). The descriptive statistics of the direct scores of the three WM components considering the age group and gender are displayed Fig. 2 and Table 3. The gender differences were due to higher direct scores of males in the CE and VSS (see Table 3).

4. Discussion and conclusions

The present study has two main objectives, the first was to replicate the linear relationship between the direct scores, expressed in standardized scores, of the WM components with age, as carried out by Gathercole et al. (2004), and the second to analyze the maturation order of the three WM components (VSS, PL and CE) that make up the multicomponent model of WM, by means of Bonferroni comparisons between the direct scores of the different age groups.

For the first objective, the main findings were that there is a linear increase with age of the direct scores of the WM three components expressed in standardized scores, as it was previously obtained in a sample between 4 and 15 years old (Gathercole et al., 2004). These authors found that in the last age group there was a tendency towards the stabilization of Z-scores, however, they did not find a differential dynamic in the order of maturation of the WM components. In the results shown in Fig. 1, a certain moderation of growth in the Z-scores of the three components can be seen as age increases, which would replicate the results obtained by Gathercole et al. (2004). However, a differential maturational dynamic between the different subtests of the three components was not reported in this study, which in part can be explained by the Z transformation, ((WM direct scores-mean of direct scores) / Standard deviation) that could be producing a certain homogenization of the data of the three components. For this reason, we propose that it would be better to work with direct scores and with a broader age range to establish the order of maturation of the WM components.

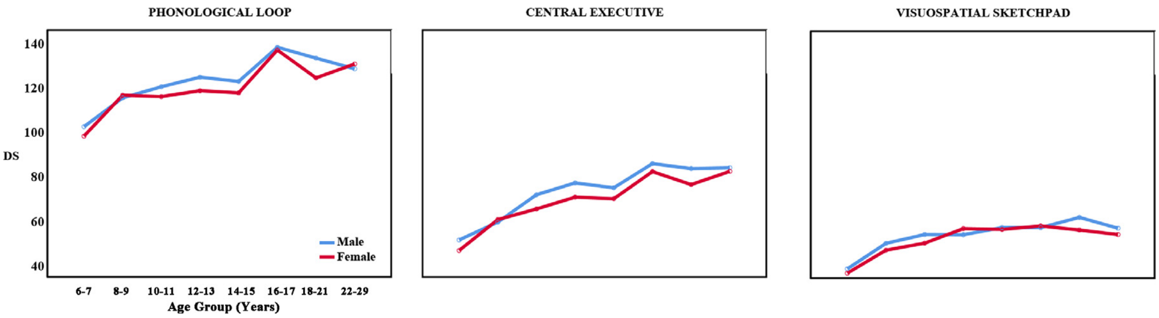

Fig. 2. Direct scores (DS) of the Phonological Loop, the Visuospatial-Sketchpad and Central Executive with respect to the age groups.

Table 2
Statistical significance of the age groups comparisons using the Bonferroni corrections for multiple comparisons.

Phonological loop

8-9	10-11	12-13	14-15	16-17	18-21	22-29	
.001	.001	.001	.001	.001	.001	.001	6-7
				.001		.020	8-9
				.001			10-11
				.022			12-13
				.012			14-15
							16-17
							18-21
							22-29

Visuo-spatial sketchpad

8-9	10-11	12-13	14-15	16-17	18-21	22-29	
.001	.001	.001	.001	.001	.001	.001	6-7
		.006	.001	.001	.001	.001	8-9
					.014		10-11
							12-13
							14-15
							16-17
							18-21
							22-29

Central Executive

8-9	10-11	12-13	14-15	16-17	18-21	22-29	
.001	.001	.001	.001	.001	.001	.001	6-7
		.001	.002	.001	.001	.001	8-9
				.001	.006	.001	10-11
						.027	12-13
				.016		.007	14-15
							16-17
							18-21
							22-29

Table 3
Descriptive statistics of direct scores of the phonological loop (PL), visuospatial sketchpad (VSS) and central executive CE), for males and females.

	1=MALE				2=FEMALE			
	Min	Max	Mean	Std	Min	Max	Mean	Std
PL	81	174	122,4	19.3	79	172	119,7	19.6
VSS	27	72	53,64	9,7	29	75	51.89	9.7
CE	37	108	73.2	16	28	106	69,25	16,1

For the second objective, the Bonferroni-type comparisons would permit to define at which age the WM direct scores would level off. The PL direct scores (verbal memory) stabilize in the 8–9 age group (with the exception of the 16–17 group that corresponded to a special situation discussed later). The latter result is coincident with the leveling off in the age group of 10–11 years obtained by Alloway et al. (2006). VSS reaches stability around 11 years and finally, the executive component is the last to mature reaching stability around 14–15 years. These results obtained with respect to the WM components maturational order contradict what was expressed in the study by Gathercole et al. (2004) of a similar maturation order of the three WM components, probably due to the fact that the age range selected by these authors ended at 15 years, and because these authors used Z-scores. The late maturation of the CE obtained in present report could be due to the slower maturation of the prefrontal cortex, since the maturation of the anterior regions such as the prefrontal cortex begins in childhood, but continues until adolescence and adulthood (Luna et al., 2010), and that activities related to executive functions are related to a variety of areas within the frontal lobes (Manoach et al., 1997; Collette and Van der Linden, 2002). The prefrontal cortex is largely responsible for executive functions because it sends and receives information through cognitive sensory and motor systems. It is divided into three parts: dorsolateral prefrontal cortex, middle prefrontal cortex, and orbitofrontal cortex (Fuster, 2002). Regarding the relationship of the prefrontal cortex with working memory, the dorsolateral prefrontal cortex is responsible for influencing activities related to planning, problem solving, working memory, etc. (Casey et al., 1997; Diamond, 2002; Fuster, 2002; Hoshi and Tanji, 2004; Konishi et al., 2002). During childhood there is an accelerated development of executive functions that is not considered linear, but has stages due to the functional and structural changes of the central nervous system (Diamond, 2001), continuing its development until the third decade of life (Tsujimoto, 2008), thus being the prefrontal cortex together with the supralimbic region the last to complete its development (Lenroot and Giedd, 2006). Therefore, the protracted maturation of prefrontal cortex would determine the late maturation of the CE.

Present results showed an anomaly in the results obtained for the age group of 16 and 17 years, a group that shows a notable increase in the PL scores. The reason for this particular result is not clear, and could be due to the recruitment of a group of brilliant subjects carried out not completely randomly for this age group, or perhaps due to a genuine effect. A larger sample size would be required to resolve this anomaly. In any case, the most plausible hypothesis is of a very early maturation of the PL given that the direct scores of the phonological loop of the oldest groups are no longer statistically significantly different from the age group of 10–11 years (except for the aforementioned group 16–17 years), a result also obtained for short-term verbal memory by Alloway et al. (2006). Furthermore, from the point of view of WM models, it has been proposed that the improvement of PL supposes a support for recoding that would improve the performance of any other type of WM, so that its maturation should precedes that of any other component (Gathercole et al., 2004).

Finally, small amplitude gender differences are observed for the VSS and CE, in which men showed a higher performance compared to women. Given the small amplitude of these gender effects and that this gender influence has not be replicated by other similar studies with larger samples (Alloway et al., 2006), or only in a few subtests (Gathercole et al., 2004), the gender differences obtained in present report must be cautiously considered.

Limitations

The peculiar result of the age group of 16–17 years old could be due to biased sampling or to a genuine WM performance burst at this age. Therefore, a replication study would be needed to confirm or reject such result."

Credit roles of authors

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

Miriam, Díaz-Palacios: Conceptualization, Data curation; Formal analysis; Methodology; Project administration; Roles/Writing - original draft; Writing - review & editing.

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.

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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