Brain and Cognition 88 (2014) 43–54

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Slow wave maturation on a visual working memory task

Catarina I. Barriga-Paulino *, Elena I. Rodríguez-Martínez, Mª Ángeles Rojas-Benjumea, Carlos M. Gómez

Human Psychobiology Laboratory, Department of Experimental Psychology, University of Seville, Spain

ARTICLE INFO

Article history:
Accepted 15 April 2014
Available online 22 May 2014

Keywords:
Working Memory
Slow Wave
Development
Delay Match-to-Sample task
Working Memory Test Battery for Children

ABSTRACT

The purpose of the present study is to analyze how the Slow Wave develops in the retention period on a visual Delayed Match-to-Sample task performed by 170 subjects between 6 and 26 years old, divided into 5 age groups. In addition, a neuropsychological test (Working Memory Test Battery for Children) was correlated with this Event Related Potential (ERP) in order to observe possible relationships between Slow Wave maturation and the components of Baddeley and Hitch's Working Memory model.

The results showed a slow negativity during the retention period in the posterior region in all the age groups, possibly resulting from sustained neural activity related to the visual item presented. In the anterior region, a positive slow wave was observed in the youngest subjects. Dipole analysis suggests that this fronto-central positivity in children (6–13 years old) consists of the positive side of the posterior negativity, once these subjects only needed two posterior dipoles to explain almost all the neural activity. Negative correlations were shown between the Slow Wave and the Working Memory Test Battery for Children, indicating a commonality in assessing Working Memory with the Slow Wave and the neuropsychological testing.

1. Introduction

Working Memory (WM) refers to a brain system that is involved in temporarily storing and manipulating information in order to perform complex cognitive tasks such as language, comprehension, learning and reasoning (Baddeley, 1992). One of the most commonly used paradigms to study WM is the Delayed Match-To-Sample task (DMTS), a S1–S2 type of paradigm where the subject has to memorize a sample stimulus at the beginning of the trial and, after a delay period, the same stimulus is presented with other different stimuli. The subject must recognize the sample stimulus and identify it from the other test-stimuli presented. Thus, several aspects of WM have to be activated: during the stimulus presentation the information to be stored has to be encoded; during the delay period the stimulus has to be retained in memory; and during the response interval the stored information (the sample) is matched with one of the presented test stimuli and induces a certain response (Low et al., 1999).

This paradigm was first employed in experimentally frontally damaged monkeys in the 1930s. The animals that had been operated on presented deficits in performing this type of task. Bilateral lesions in this cerebral structure produce a severe deficit in performing this type of task, indicating a direct relationship between the prefrontal cortex and the delayed response tasks (Funahashi & Kubota, 1994). Thus, this task was established as a good paradigm for studying the prefrontal functions (Wang, 2005). To evaluate the consequences produced in WM due to lesions in the dorsolateral prefrontal cortex (DLPFC), Goldman-Rakic (1971) submitted infant and adult monkeys to a WM task after damaging their frontal cortex. The author found that the youngest monkeys performed the task correctly, while the adult monkeys did not. This result would indicate that at younger ages this kind of task is performed by cerebral structures other than the DLPFC. Moreover, when the younger monkeys grew up, they had worse performance than when they were infants, probably because the transference of this cognitive function to the DLPFC was problematic due to this existing lesion in that particular cerebral region. This latter result suggests a dynamic arrangement of the brain areas dedicated to a certain function during development.

WM improves with age. Luciana, Conklin, Hooper, and Yarger (2005) analyzed nonverbal tasks, including a spatial delayed response, in subjects between 9 and 20 years old. They observed that the performance of the oldest group (18–20 years old) was significantly better than that of the younger groups (9–10, 11–12 and 13–15 year-old). When two delay interval levels were

---

* Corresponding author. Address: Human Psychobiology Laboratory, Department of Experimental Psychology, University of Seville, Calle Camilo José Cela, s/n, 41018 Seville, Spain. Fax: +34 954551784.

E-mail address: cbarriga@us.es (C.I. Barriga-Paulino).

http://dx.doi.org/10.1016/j.bandc.2014.04.003
0278-2626/© 2014 Elsevier Inc. All rights reserved.

analyzed (500 and 8000 ms), the authors found that the younger group (9–10 years old) was significantly less accurate on long delays (8000 ms) than the other age groups, who did not differ from each other, indicating that this capability did not index developmental changes after ages 11–12.

Using a DMTS paradigm with 6 delays of from 1 to 32 s, Paule et al. (1998) found that normal development affects the response latency, encoding, and retention of the stimulus. They reported an improvement in accuracy (more correct responses) and in RTs (they became faster) as the age increased. On the other hand, the variability among subjects decreased with age. Moreover, younger children presented worse retention of the stimulus, and the older children were more accurate in recognizing the correct stimulus after the shorter delay (1 s), indicating a better encoding of the stimulus to memorize.

With regard to neuropsychological tests for assessing WM, Gathercole, Pickering, Ambridge, and Wearing (2004) reported that the basic tripartite modular structure of WM is present from 6 years of age. These authors observed that all the tests used in their study, the majority from the Working Memory Test Battery for Children (WMTB-C), showed a linear increase from 4 to 14 years of age. This test consists of nine subtests designed to tap the three main components of WM (phonological loop, visuospatial sketchpad and central executive), based on the Baddeley and Hitch WM model, one of the most prevalent WM models.

The maturation of WM depends on several aspects, among them, the type of information to be stored, the information's encoding and retention, and the changes related to the maturation of the executive functions, which mainly involve the prefrontal cortex. Neuroimaging studies have shown that in WM processing in children between 7 and 12 years old, similar cerebral structures to those used by adults are involved, including the prefrontal cortex, although with a lower level of activation (Klingberg, 2006; Kwon, Reiss, & Menon, 2002; Nelson et al., 2000). An increased WM capacity with increasing age and brain activity has been described. Klingberg, Forssberg, and Westerberg (2002) found a positive relationship between WM capacity and brain activity, with older children presenting greater activity. This relationship would be associated with a more stable and interference-resistant delay activity.

Several ERP studies, using the S1–S2 paradigm, have shown a negative slow wave during the stimulus retention period on WM tasks (Ruchkin, Johnson, Canoune, & Ritter, 1990; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992), whose amplitude and cerebral topography differ according to the modality and the type of information to be retained (Barceló, Martín-Loeches, & Rubia, 1997; Drew, McCollough, & Vogel, 2006). Thus, slow waves present more amplitude in the left hemisphere during phonological memory operations (Barrett & Rugg, 1990; Rugg, 1984a; Rugg, 1984b) and more amplitude in the right hemisphere during visual memory operations (Barrett & Rugg, 1989; Barrett, Rugg, & Perrett, 1988). This component has also been shown to be sensitive to task difficulty (Ruchkin et al., 1992), and it seems to present a different topographical distribution for spatial WM and object memorization tasks (Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1997). Visual memorization is generally associated with a center-posterior negativity (Patterson, Pratt, & Starr, 1991; Ruchkin et al., 1992), and, particularly, object memorization has been observed as great negativity in the fronto-medial area during the retention period of that object (Mecklinger & Pfeifer, 1996). However, opposite results were described by Low et al. (1999), who found, on a visual DMTS task and after the S1 presentation, a negative slow wave with 500 ms duration over the right posterior area. Based on several investigations, Berti, Geissler, Lachmann, and Mecklinger (2000) suggested that frontal activity could reflect control processes or motor preparation, while the negative slow potentials observed in the parieto-occipital area would reflect activity related to stimulus storage. The Slow Wave (SW) is probably related to the sustained neurophysiological activity in neurons of prefrontal and temporal cortices during visual DMTS tasks (Fuster & Jervey, 1982; Goldman-Rakic, 1995).

McCollough, Machizawa, and Vogel (2007) used a variation of the DMTS paradigm, where the subjects visualized stimuli in both visual hemi-fields but were instructed to memorize only those presented in one half of the screen indicated by an arrow. These authors described a negative activity during the delay period that occurred after 200 ms of the stimuli onset. This potential was observed in the contralateral hemisphere with respect to the location of the memorized stimuli, an effect the authors called *Contralateral Delay Activity* (CDA). This wave presented a topography in which the maximal amplitude is located in the parieto-posterior region (Woodman & Vogel, 2008) and modulated by the number of items present in the display to memorize: there is an increase in amplitude with the number of stimuli stored in memory. As far as we know, the developmental trajectory of the WM slow wave has not been traced, although recently the presence of the CDA was described in limited samples of children and adolescents (Sander, Werkle-Bergner, & Lindenberger, 2011; Spronk, Vogel, & Jonkman, 2013).

In this paper, we intend to analyze the ontogenetic evolution of the SW existing in the delay period on a visual DMTS task. The presence of SW in children would support similar mechanisms in adults to maintain visual items during the delay period. Additionally, the relationship of this neurophysiological signal with WM maturation, as measured by the WMTB-C, will be assessed, in order to detect a possible more general role of the functional meaning of the SW in WM.

2. Method

2.1. Subjects

One-hundred and seventy subjects between 6 and 26 years old participated in this study (15.89 years ± 6.116). For each year, 8 subjects were recorded and analyzed (4 males and 4 females), with a total of 85 males and 85 females. However, two subjects were excluded because they did not present clear ERPs; therefore, the final sample was composed of 168 subjects.

Subjects did not report any neurological diseases or psychological impairments. Both groups were extracted from middle class socioeconomic backgrounds. The children had normal academic records, and the young adults were college students. Younger subjects were recruited from public schools, and young adults were recruited through advertisements on the university campus. Experiments were conducted with the informed and written consent of each participant (parents/tutors in the case of the children) following the Helsinki protocol. The study was approved by the Ethical Committee of the University of Seville.

2.2. Stimuli, tasks and procedures

Visual stimuli were cartoons inserted in the category of Pokemons and Digimons. The size of all stimuli was adapted in Picassa to equal dimensions of 142 × 228 pixels. Uncommon stimuli were used to avoid verbal strategies and to ensure that memorization processing was mainly visual.

The stimulation program used was E-Prime version 2.0, and a SRBOX Cedrus was used for the subjects' responses.

The paradigm used was a DMTS task composed of a total of 128 trials organized in 4 experimental blocks with 32 trials each, which were counterbalanced; i.e., in half of them the target stimulus