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Brain dynamics of attention and working memory engagement in subitizing

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ABSTRACT

This study addressed the engagement of attention and working memory, as inferred from electrophysiological measurements, in the processing of small sets of objects. We recorded N2pc and CDA, two lateralized components of the EEG signal associated respectively with individuation and visual working memory, while participants enumerated a variable number (1–9) of uniquely colored targets among distractors. Behavioral results showed a clear subitizing effect, with lower error rates for smaller (1–3 targets) than larger sets. ERP results showed that both N2pc and CDA amplitudes increased as a function of target numerosity up to approximately three targets. However, individual differences in the enumeration efficiency were correlated only with the individual variation in the N2pc modulations. The results suggest that the constraints of the attentional individuation system play a significant role in the occurrence of the subitizing phenomenon.

1. Introduction

Decades of behavioral research has indicated that humans are very accurate and fast when enumerating small set of objects, up to approximately three–four elements (Kaufman et al., 1949; Mandler and Shebo, 1982; Trick and Pylyshyn, 1994). This phenomenon is known as subitizing and it is signaled by the presence of an inflection point in the behavioral data function, corresponding to a sudden change in the enumeration slope. This inflection point is considered as the signature of the existence of two different ways of processing small and large numerosities (but see Whalen et al., 1999 for a different account). Neuroimaging experiments have provided support for this distinction by showing different brain activations associated with the enumeration of small versus large object quantities (Ansari et al., 2007; Vuokko et al., 2013). Additionally, studies on patients have reported dissociations in processing small and large quantities of objects (Dehaene and Cohen, 1994; Demeyere et al., 2012).

Despite the large number of studies on the subitizing phenomenon the nature of small-numerosity processing remains elusive. There are at least two contending accounts of the subitizing effect (e.g. Feigenson et al., 2004; Leslie et al., 1998; Trick and Pylyshyn, 1993; Whalen et al., 1999). On one account (Cavanagh and He, 2011; Trick and Pylyshyn, 1994), subitizing reflects a limitation in the simultaneous individuation of multiple objects. While early proposals (e.g. Trick and Pylyshyn, 1993) argued that individuation operates pre-attentively, there is growing consensus that it is one of the key functions of attention. Therefore, capacity limits of the

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attentional functions could play a key role in the subitizing phenomenon. In line with this explanation, recent studies have indicated that enumeration accuracy for small target numerosities varies with modulations of the attentional load (e.g. Egeth et al., 2008; Railo et al., 2008; Vetter et al., 2008). Support for this account has also come from neuroimaging studies (Ansari et al., 2007; Vetter et al., 2011), which have shown differential modulation of the temporo-parietal junction, a region previously linked to exogenous attention (e.g. Corbetta and Shulman, 2002), for small versus large target numerosities.

An alternative explanation of subitizing considers this effect as the result of late, capacity-limited processes related to visual working memory (Cowan, 2001; Feigenson et al., 2004; Feigenson, 2011). This account is based on the idea that working memory may be crucial for maintaining active the representations of individual items during the process of mapping the set of elements onto a specific numerical value. Since visual working memory is limited in capacity (Cowan, 2001) only a limited number of representations can be maintained active simultaneously, thus generating the subitizing effect. The working memory account of subitizing is inspired by previous research on multiple objects discrimination in infants and animals. In these studies participants choose between two groups of objects that were previously hidden behind a screen simultaneously (e.g., Rugani et al., 2009) or, in other paradigm (e.g., Feigenson and Carey, 2003, 2005) they search for objects that were sequentially hidden in a box. Results indicate that both infants and animals are able to retrieve correctly all the objects or to choose the larger amount of items only when their number does not exceed three or four, thus suggesting that they possess the ability to discriminate small numerosities. Support for the working memory account of subitizing is provided by a recent study on human adults that has found that individual differences in a working memory task are correlated with individual variations in the subitizing limit (Piazza et al., 2011; but see Tuholski et al., 2001). In that study participants had to count a variable number of items while maintaining two or four objects in visual working memory for a delayed match-to-sample judgment. The individual subitizing range varied as a function of the number of objects to be maintained in visual working memory, suggesting that this mechanism may have a significant role in the subitizing phenomenon.

In the present study, we used an electrophysiological approach to investigate the contributions of multiple object individuation and working-memory processes on subitizing. The high temporal resolution of EEG affords the opportunity to investigate temporally dissociable processes such as object individuation and visual working memory, which are assumed to operate in sequence and have therefore separate time courses. Using this approach, it is possible to address directly the involvement of these temporally separated mechanisms in enumeration of small quantities in a single task, without having to introduce a secondary task to probe the involvement of a specific process (attention versus VWM) on the subitizing effect. We focused on N2pc and CDA, two neural indexes that have been recently shown to track, respectively, individuation of multiple objects and their maintenance in visual working memory.

N2pc (N2 posterior contralateral) is a transient component of the ERPs that is recorded around 200 ms post-stimulus onset from the posterior electrodes contralateral to the side of presentation of lateralized targets (Eimer, 1996; Luck and Hillyard, 1994). The N2pc is considered to be the neural reflection of target selection (either through target enhancement or distracter suppression) and is elicited in a variety of tasks, ranging from present/absent judgments to visual discrimination and multiple object tracking (Drew and Vogel, 2008; Mazza et al., 2009a, 2009b). Recent studies on enumeration (Ester et al., 2012; Mazza and Caramazza, 2011; Mazza et al., 2013; Pagano and Mazza, 2012) have found that the N2pc amplitude changes as a function of target numerosity. For instance, Ester et al. (2012) found that the amplitude of N2pc was modulated by the number of targets to be enumerated, increasing up to three items and then reaching an asymptote for larger numerosities. This result suggests that subitizing depends on constraints operating at the individuation stage where only a limited number of objects can be individuated simultaneously (Pylyshyn, 1989; Trick and Pylyshyn, 1993).

CDA (Contralateral Delay Activity; also called SPCN, Sustained Posterior Contralateral Negativity) is a sustained negativity elicited at approximately 400 ms post-stimulus onset from posterior sites contralateral to the side of the target (Robitaille et al., 2009; Vogel and Machizawa, 2004). This component has been recorded mainly in delayed match-to-sample tasks during the maintenance phase (Ikkai et al., 2010; McCollough et al., 2007; Vogel and Machizawa, 2004) or in multiple object tracking tasks during the tracking period (Drew et al., 2012; Drew and Vogel, 2008). The CDA amplitude is also modulated by the number (up to 3–4) of objects that must be maintained in visual working memory, suggesting that this component reflects a capacity-limited mechanism that maintains active multiple visual representations (Vogel and Machizawa, 2004).

To assess the role of both individuation and visual working memory in subitizing here we asked participants to count an extended range of target numerosities (1, 2, 3, 4, 5, 6, 7, 8 and 9) while recording N2pc and CDA. We evaluated the involvement of N2pc and CDA in subitizing by concentrating on three key aspects of the electrophysiological activity.

First, we focused on the modulations of N2pc and CDA in response to changes in the number of targets to be enumerated. If both individuation and working memory are involved in simultaneously processing multiple targets during enumeration, both the N2pc and CDA should be modulated by the number of targets presented in the visual field. Second, given the limit in the number of objects that can be "subitized", we predicted that we should observe an inflection point in the neural mechanism(s) that underlies the subitizing phenomenon, a sort of "neural subitizing effect". For this reason, we assessed for the presence of an inflection point in the electrophysiological response (see also Ester et al., 2012). To anticipate, here we focused on a subset of target numerosities (1–5) instead of taking into account the whole range (1–9). This was done to make our results comparable to the extant ones (Ester et al., 2012). Third, we evaluated which of the mechanisms (individuation or working memory, or both) better reflects the subitizing phenomenon by focusing on the correspondence between individual differences in the behavioral subitizing and individual differences in the neural