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Brief article

Keeping an eye on serial order: Ocular movements bind space and time

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ABSTRACT

The present study examined whether traveling through serially-ordered verbal memories exploits overt visuospatial attentional resources. In a three-phase behavioral study, five single-digits were presented sequentially at one spatial location in phase 1, while recognition and verbal recall were tested in phases 2 and 3, respectively. Participants' spontaneous eye movements were registered along with the verbal responses. Results showed that the search and the retrieval of serially-ordered information were mediated by spontaneous ocular movements. Specifically, recognizing middle items of the memorized sequence required longer inspection times and, importantly, a greater involvement of overt attentional resources, than recognizing the serially first-presented item and, to a lesser extent, the last-presented item. Moreover, serial order was found to be spatially encoded from left-to-right, as eye position during vocal responses deviated the more to the right, the later the serial position of the retrieved item in the sequence. These findings suggest that overt spatial attention mediates the scanning of serial order representation.

1. Introduction

People's ability to maintain and recall the order of events or elements in a sequence is a key function of working memory (WM) (Baddeley, 1992; Lashley, 1951). Among others, this capacity is fundamental to comprehension, learning, and reasoning (Baddeley, 2012). Given its importance in human cognition, over the past years different models have been dedicated to account for memory for serial order. In particular, according to a predominant class of models (i.e., position marking models) the serial order within WM would follow from the pairing of items with some external representation of their location within the sequence (e.g., Brown, Preece, & Hulme, 2000; Henson, 1998), rather than from a mere pairing between the items themselves (e.g., Lewandowsky & Murdock, 1989). In the wake of the position marking models, Abrahamse, van Dijck, Majerus, and Fias (2014) recently claimed that serial order would be grounded on the spatial attention system. More specifically, the position of ordered elements to be remembered would be translated into internal spatial coordinates and, thus, into a spatial representation (Abrahamse et al., 2014). Importantly, the manipulation of this serial order representation would engage spatial attention resources and, in turn, retrieval of memorized items would result from a selection operated by spatial attention mechanisms (Abrahamse et al., 2014).

According to this hypothesis, recent evidence has shown that serially-ordered verbal information is encoded along a spatial dimension (Previtali, de Hevia, & Girelli, 2010; van Dijck & Fias, 2011) and that covert spatial attentional resources are recruited to access to this serial order representation (van Dijck, Abrahamse, Majerus, & Fias, 2013). In particular, short sequences of numbers and words memorized in WM were found to be associated to space: items presented at the beginning of the memorized sequence were responded to faster with the left hand-side, while items from the end were responded to faster with the right hand-side (van Dijck & Fias, 2011). Moreover, retrieving an item from an ordered sequence has been shown to be mediated by covert spatial attention (van Dijck et al., 2013), since the detection of a visual target appearing in the left or in the right side of the space was modulated by the serial position of a previous memorized item acting as a prime. Specifically, the later the position of an item in the memorized sequence, the faster the detection of the target in the right side of the space (van Dijck, Abrahamse, Acar, Ketels, &

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Fias, 2014; van Dijck et al., 2013). The functional involvement of spatial processing in serial order was confirmed in a recent study where retrieval was found to be facilitated by visuospatial priming and, more specifically, by task-irrelevant exogenous spatial cues (De Belder, Abrahamse, Kerckhof, Fias, & van Dijck, 2014).

Similar space–time interactions have been also described for overlearned temporal information (Ouellet, Santiago, Funes, & Lupiánez, 2010; Santiago, Lupáñez, Pérez, & Funes, 2007; Torralbo, Santiago, & Lupiáñez, 2006; Weger & Pratt, 2008), supporting more generally the view that temporal order is represented along a spatial continuum. According to these spatio-temporal interactions, parietal and frontal cortex largely involved in attention control, participate in memory for order information (Koenigs, Barbey, Postle, & Grafman, 2009; Marshuetz, 2005; Marshuetz & Smith, 2006). A tight connection between space and time, indeed, pervades our daily experience. Events occur at a certain time and in a certain spatial context throughout life. As time is less graspable than space, temporal concepts are grounded in spatial experience (Torralbo et al., 2006; for review see Bonato, Zorzi, & Umiltà, 2012). Hence, we frequently borrow from the language of space when describing duration ("a short break") or event location ("in the distant past"), and we make use of related words to indicate the order of events ("before") in both spatial and temporal contexts.

However, although attention can move in space covertly, i.e., without eye movements, or overtly, with eye movements (Posner, 1980), this distinction has been widely challenged by recent findings indicating that also covert attentional processes are tightly linked to oculomotor processes (Corbetta, 1998; Corneil & Munoz, 2014; Engbert & Kliegl, 2003). Yet, evidence supporting overt spatial attention in mediating between space and serial order is still missing. Indeed, while previous studies have shown that covert spatial attention is engaged in accessing the serial representation, there is no direct proof of sensorimotor changes in overt orienting during serial processing. This is an important omission, since earlier reports already suggested a possible involvement of spontaneous oculomotor strategies in the processing of ordered verbal information (Robertson, 1990; Weinberg, Diller, Gerstman, & Schulman, 1972). In the present study, we therefore hypothesized that the scanning of a serial representation would be accompanied by spontaneous eye movements. This hypothesis was based on two main observations. First, recent findings have shown that the scanning of an internal representation goes along with a concurrent sensorimotor scanning (e.g., Loetscher, Bockisch, & Brugger, 2008; Loetscher, Bockisch, Nicholls, & Brugger, 2010). These studies hark back to the general idea that oculomotor processes involved in visual scanning are also crucial for the mental scanning of visual images (Hebb, 1968). Second, and more importantly, the left-to-right orientation of the serial representation might be grounded on sensorimotor mechanisms and, more specifically, on reading and writing practices (Abrahamse et al., 2014). Indeed, oculomotor routines involved in both reading and writing would result, through repetition, in a preferential directional scanning of the external space (see Rinaldi, Di Luca, Henik, & Girelli, 2014). This directional preference would be reinforced in Western populations, where reading occurs from left-to-right, by the slight leftward bias in visuospatial attention processing (Bowers & Heilman, 1980; see Abrahamse et al., 2014; de Hevia, Girelli, & Macchi Cassia, 2012). On these grounds, we hypothesized that, if serial order is grounded on sensorimotor processes, eye movements concurrent to the retrieval of ordered information should reflect the internal scanning of its spatial representation.

To address this issue, we conducted a three-phase study. In the first phase, five random digits (sampled from the range 1–10), i.e., the positive set, presented sequentially at the center of the screen had to be memorized in correct order by participants. In the second phase, all digits from 1 to 10 were randomly presented twice at the central position and participants had to decide whether a digit, i.e., the probe, was a member of the positive set or not ("recognition"). In this phase, we thus adopted a fixed-set procedure, with the same positive set that was tested for multiple trials (Sternberg, 1966, 1975). Finally, participants repeated the memorized sequence ("recall"). Participants were required to respond verbally in both the recognition and the recall phases. Importantly, to investigate the role of the oculomotor system in mediating between space and serial order, we measured spontaneous eye movements at the onset of the verbal response.

In the recognition phase, we first predicted that reaction times should vary as a function of the item's serial position in the memorized sequence. Specifically, lower reaction times should characterize the recognition of the serially first and last items, showing the presence of a primacy and a recency effect, respectively (Corballis, 1967). This hypothesis was based on the assumptions of the Start–End Model for serial order (Henson, 1998), according to which the encoding of order information consists in the storage of episodic tokens, that incorporate positional representations in a specific spatiotemporal context. More precisely, this positional coding assumes that the first and the last items of a sequence are the most salient elements (Henson, 1998). Accordingly, various studies have found faster responses for serially-presented first and last items (e.g., Burrows & Okada, 1971; Corballis, 1967; Corballis, Kirby, & Miller, 1972). Despite a long-standing debate on the presence of primacy and recency effects, contrasting results are widely accounted for by methodological differences (see Sternberg, 1969; see also McElree & Dosher, 1989).

Second, and critically, if overt spatial attention mediates the search and the retrieval of serially-ordered items, eye movements should also unveil the presence of primacy and recency effects. This should be reflected by a greater involvement of overt attentional resources, i.e., larger eye movements, for the middle items. Indeed, since there is possible representational overlap between middle items (Henson, 1998), the search and the retrieval of these elements would be more demanding, i.e., requiring more visuospatial attentional resources. Contrarily, the first and last items would represent respectively the leftmost and the rightmost endpoint of the spatial array and their search would, consequently, require less attentional orienting. Since serial order is represented along a horizontal plane (Abrahamse et al., 2014; see also Bonato et al., 2012), we hypothesized that accessing to such a representation should be mediated mainly by horizontal eye movements. Furthermore, according to recent findings (van Dijck et al., 2013, 2014), we also explored whether the recognition of the first element would induce a leftward overt attentional shift, while the recognition of the last element would induce a rightward shift.

Finally, if serial information is spatially encoded in a left-to-right format, eye position during recall should correspondingly deviate more to the right, the later the item position in the sequence. The systematic involvement of oculomotor mechanisms during sequence recall would support the hypothesis that serial order is grounded on visuospatial attention. Indeed, scattered evidence for the spatial representation of serial order was already collected by Harcum (1975). More recently, it has been inferred from a dichotomous response-setting, i.e., response time differences between left and right responses to memorized items (van Dijck & Fias, 2011), or from a dichotomous visual-setting (van Dijck et al., 2013, 2014), i.e., response time difference to lateral targets primed by memorized items. Thus, a possible left-to-right shift of eye position during recall would provide the first direct evidence that memorized items are ordered in a continuous space.