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Attentional refreshing of information in working memory: Increased immediate accessibility of just-refreshed representations ☆

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ABSTRACT

Working Memory (WM) keeps information temporarily accessible for ongoing cognition. Refreshing is a proposed mechanism to keep information active in WM, by bringing memory items into the focus of attention. We report five experiments in which we examined the local effects of refreshing. Participants were either instructed to refresh (to think of) the different memory items at an imposed pace after list presentation, so that we had experimental control over which item was being reactivated in the focus of attention at different points in time during retention, or were free to spontaneously use refreshing (or not). We present evidence for (1) the presumed local effect of refreshing that is heightened accessibility of the just-refreshed item, (2) the use of speeded responses to WM probes as a direct, independent index of the occurrence of refreshing, and (3) spontaneous occurrence of refreshing of to-be-remembered information during slow list presentation and during an empty delay following list presentation.

Introduction

Working memory (WM) is a limited-capacity system that keeps information temporarily accessible for ongoing thought and action and is, as such, typically considered a keystone of human cognition. Despite broad consensus on the importance of WM for goal-directed cognitive activities such as learning, reasoning, problem solving, language comprehension and mental arithmetic (e.g., Barrouillet, 1996; Daneman & Merikle, 1996; DeStefano & LeFevre, 2004; Engle, Cantor, & Carullo, 1992; Halford, Wilson, & Phillips, 1998; Harrison, Shipstead, & Engle, 2015; Kyllonen & Christal, 1990; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002), there is currently little agreement on how WM works.

One central issue that remains heavily debated is the cause of forgetting and the mechanisms that can counteract the loss of information from WM. According to one view on WM, to-be-remembered information is lost from WM because it decays over time (the temporal decay account; see Ricker, Vergauwe, & Cowan, 2016, for a recent review) and this time-based forgetting can be counteracted by reactivating the representations of the to-be-remembered information (e.g., Baddeley, 2000; Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet & Camos, 2012; Cowan, 1992; Cowan, 1995; Vergauwe & Cowan, 2014). This reactivation process is assumed to use the focus of attention to counteract forgetting and is typically referred to as *refreshing* (Barrouillet et al., 2007; Johnson, Reeder, Raye, & Mitchell, 2002). A good, precise understanding of refreshing is crucial towards pitting decay accounts of WM against other accounts of WM, such as accounts in terms of interference (see Oberauer, Farrell, Jarrold, Pasiecznik, & Greaves, 2012, for a recent review), temporal distinctiveness (Brown, Neath, & Chater, 2007) or displacement from WM (Waugh & Norman, 1965; see also Atkinson & Shiffrin, 1968; James, 1890). But also, and more generally, a good understanding of refreshing is important towards a better understanding of how WM works. Studies that specifically aim at isolating, measuring and detailing the process of refreshing are scarce. With this in mind, the present study proposes a detailed examination of refreshing. Specifically, the presumed local effects of refreshing on WM representations are examined, and a new way of assessing whether refreshing has occurred or not is proposed.

Attentional refreshing

Refreshing refers to an attention-based maintenance process in WM. It is assumed to be similar in many respects to verbal rehearsal but there are some key differences. Whereas refreshing is assumed to rely on attentional reactivation of memory traces,

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verbal rehearsal is assumed to rely on subvocal articulation of verbal information. Thus, whereas refreshing is assumed to be an attentional maintenance mechanism that can be used to maintain verbal, but also visuo-spatial, information, rehearsal is assumed to be a speech-related maintenance mechanism that can only be used to maintain verbal information. In contrast to refreshing which is by definition an attention-based process, verbal rehearsal is typically assumed to not, or only minimally, rely on attention (e.g., Baddeley & Logie, 1999; Camos & Barrouillet, 2014; Chen & Cowan, 2009; Naveh-Benjamin & Jonides, 1984). Accordingly, behavioral, developmental and neuroimaging studies strongly suggest that refreshing and verbal rehearsal are two independent maintenance processes (e.g., Camos, Lagner, & Barrouillet, 2009; Cowan et al., 1998; Hudjetz & Oberauer, 2007; Loaiza & McCabe, 2012; Oftinger & Camos, 2016; Raye, Johnson, Mitchell, Greene, & Johnson, 2007; Vergauwe, Camos, & Barrouillet, 2014).

Though considerable research has been devoted to the process of refreshing over recent years, little is currently known about how refreshing operates to support the maintenance of a set of elements in WM. There seems to be general agreement that the process operates by bringing WM representations into the focus of attention (Barrouillet & Camos, 2012; Cowan, 1995; Higgins & Johnson, 2009; Vergauwe & Cowan, 2014, 2015) and that the act of refreshing, or "thinking of", results in information becoming highly accessible again in WM. This, in turn, is proposed to protect the information from being forgotten. Consistent with this idea, it has been shown that (1) decreasing the time available for refreshing, by manipulating the attentional demands of a secondary task to be performed during a retention interval, results in poorer memory performance (e.g., Barrouillet, Portrat, & Camos, 2011; Barrouillet et al., 2004, 2007; Camos & Portrat, 2015; Hudjetz & Oberauer, 2007; Ricker & Cowan, 2010; Vergauwe, Barrouillet, & Camos, 2009; Vergauwe, Barrouillet, & Camos, 2010; but see Oberauer & Lewandowsky, 2013; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012), and (2) increasing the number of times a memory item has been refreshed, by presenting cues prompting participants to think of specific WM items during a retention interval, results in better memory performance for that item (Souza, Rerko, & Oberauer, 2015). In these studies, researchers have focused on the effects of refreshing on memory performance at the end of the trial or at the end of the experimental session. Here, we propose an alternative approach to advance our understanding of refreshing. Rather than examining the effects of refreshing on the final outcome that is memory performance, we aim at examining the presumed effects of refreshing more locally.

The local study of refreshing

One of the first studies to examine the effect of refreshing more locally was done by Vergauwe et al. (2014). In that study, we examined the effect of refreshing on response times (RTs) in a secondary task performed during retention. A short series of to-be-recalled items was followed by a fixed retention delay during which a secondary task was to be performed. The number of to-be-remembered items was varied and we observed that RTs in the secondary task increased as a direct function of the number of items to be remembered (i.e., set size). This pattern indicated that participants spontaneously engaged in refreshing during the retention interval and that refreshing postponed responses in the secondary task, with each additional to-be-remembered item resulting in an additional postponement. Importantly, this was observed for verbal material under articulatory suppression, thereby minimizing the use of verbal rehearsal, and for visuospatial material. While we interpreted this pattern as clear evidence for spontaneous refreshing, it was argued that our interpretation of the RT-set size functions was heavily dependent on the theoretical framework within which the study was designed (i.e., the Time-Based Resource-Sharing model; Barrouillet et al., 2004, 2007). In particular, an interpretation of the RT-set size functions in terms of postponement of concurrent processing because of spontaneous refreshing only holds under the assumption that processing and refreshing rely on a common resource that has to be shared in a time-based, sequential way. As such, it has been argued that the Vergauwe et al. (2014) study does not provide independent, direct evidence for refreshing in WM (Lewandowsky & Oberauer, 2015).

In the current study, we aim at testing the refreshing hypothesis in a more direct and independent way. Therefore, we propose to focus on the local effect of refreshing on the WM representations of the to-be-remembered information during retention, rather than on secondary task performance during retention. As we will explain below, this enabled us to use a simpler design and to rely on assumptions that are not specific to refreshing-based accounts of WM.

The local effect of refreshing on WM representations

To maintain a list of items, refreshing is assumed to operate serially, with the focus of attention cycling from one item to the next (e.g., Barrouillet & Camos, 2012; Cowan, 2011; McCabe, 2008; Nee & Jonides, 2013; Vergauwe et al., 2014). The item that is represented in the focus of attention is assumed to be in a privileged state of heightened accessibility (e.g., Basak & Verhaeghen, 2011; Cowan, 1995; McElree, 2006; Nee & Jonides, 2008; Oberauer & Hein, 2012). The presumed local effect of refreshing on WM representations is thus the heightened accessibility of the just-refreshed WM representation. This state of heightened accessibility of the information brought back into the focus of attention has not yet been empirically demonstrated. That is, while there is evidence for a special status of the item in the focus of attention (Garavan, 1998; Oberauer, 2002; see Oberauer & Hein, 2012, for a recent review), there is little or no evidence that this special status applies in the situation when information is refreshed. Providing such evidence was one of our main aims in the current study.

Consistent with the idea of heightened accessibility of the information in the focus of attention, it has been shown that the status in WM of the final item of a memory list is qualitatively different from that of the other to-be-remembered items. For example, in an item-recognition task in which a list of items is followed by a probe to be judged present in or absent from the list of items, it is typically observed that RTs to the last-presented item are faster than to any other item of the list (e.g., Burrows & Okada, 1971; McElree & Dosher, 1989; Nee & Jonides, 2008; Öztekin, Davachi, & McElree, 2010). The idea is that, at the end of the memory list, the final item is maintained in the focus of attention, resulting in speeded responses to probes that match that item. However, a last-presented RT benefit is not always observed in item-recognition (e.g., Clifton & Birenbaum, 1970; Donkin & Nosofsky, 2012; Sternberg, 1966) and recent research suggests that responses to the last-presented item and access to the focus of attention might be dissociable (e.g., Morrison, Conway, & Chein, 2014).

In a recent study, we assumed that speeded responses do not need to be invariably tied to the last-presented item, and tested whether the last-presented benefit in RT can be leveraged and used as an independent, more direct index to assess if refreshing had occurred (Vergauwe et al., 2016). Specifically, we reasoned that, when refreshing occurs, the last-presented item is replaced by another list item in the focus of attention, and thus, speeded responses should no longer be observed for the last-presented item. In four experiments, short series of red letters were