Multiple states of working memory

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General Discussion

Working memory (WM) is a cognitive system that enables the maintenance and manipulation of information that is no longer present in our environment. As such, WM plays a crucial role in goal-directed behavior as it is mandatory for any task that requires conscious access to previously perceived information. Since only a limited amount of information can be represented in WM at a given moment (Cowan, 2010), it is crucial to encode and maintain information that is relevant to our current behavioral goals and to remove information that is no longer relevant. How information is encoded, maintained and deactivated in WM are therefore key questions in understanding human information processing.

The studies documented in this thesis investigated how various manipulations influence the encoding, maintenance, and deactivation of information in WM. To this end, we used the memory-driven attentional capture effect as an index of WM activation. This effect refers to the finding that attentional selection can be biased by the content of WM, such that the activation of information in WM increases the likelihood that attention will be drawn towards matching information in the environment (Downing, 2000; Gao et al., 2016; Olivers, 2009; Olivers et al., 2006; Pan, 2010; Soto et al., 2005; Soto & Humphreys, 2007). Therefore, the activation of a representation in WM can be assessed by determining whether visual attention is deployed to an object that matches this representation.

With regard to the encoding of information in WM, the studies documented in this thesis present several findings of interest to understanding how different task demands influence the establishment and strength of a representation in WM. To start, the study reported in Chapter 5 shows that attention can be used to selectively encode a specific feature of an object. Specifically, in this study, participants were precued as to whether the shape or the color of a subsequently shown object had to be encoded in WM. Next, participants performed a visual search task in which one of the distractors could match the shape or color of the earlier shown object. The results showed evidence for attentional capture by distractors that matched the color of the earlier shown object, but only when this color was precued as the relevant feature, thus demonstrating that during perception, attention can act as a gate that determines which feature of an object is stored in WM. Such selective encoding of individual object features fits well with previous findings showing that the requirement to select one feature of an object for representation in WM does not automatically lead the other features of this object to be encoded as well (Chen & Wyble, 2015; Chen, Swan, & Wyble, 2016; Olivers et al., 2006). Another finding that illustrates the modulatory role of task demands in transferring information to WM can be found in the study reported in Chapter 2. In this study, we found that deep encoding (i.e., extracting the meaning of a word) results in attentional capture by a matching picture in a subsequent RSVP task, whereas shallow encoding (i.e., judging whether the word is written in uppercase or lowercase) does not result in capture. Importantly, in this study, participants were not asked to remember the words. Accordingly, this finding suggests that the requirement to access the meaning of a word for a conscious judgment requires WM activation, which in turn guides visual attention towards a picture depicting the referent of this word. Taken together, the results presented in this thesis demonstrate that mechanisms of attentional selection can act as filter for the information that is represented in WM (Chapter 5) and they make clear that the requirement to access the meaning of a word requires the activation of that word in WM (Chapter 2).

With regard to the maintenance of information in WM, the work collected in this thesis shows how interference that arises from performing another task can modulate the activation of representations held in WM. Specifically, in the study reported in Chapter 2, we found that attentional capture by pictures that correspond to a word that has previously undergone deep encoding is eliminated when the word is followed by a memory-encoding task, thus suggesting that this activation can be overwritten by new information in WM. The study reported in Chapter 3 extends these findings by showing that whereas capture produced by residual WM activation is abolished when observers have to execute a secondary task after processing the word, the requirement to remember the word leads to capture regardless of the presence of the secondary task. This finding suggests that the requirement to remember the word allowed the representation of this word to be reactivated in WM after processing intermediate task. Taken together, these findings indicate a difference between residual versus goal-driven WM activation. While goal-driven WM activation can be reinstated after dual-task interference, residual WM activation will be lost due to dual-task interference.

Lastly, the studies documented in this thesis also address the extent to which people are capable of removing a no longer relevant object or feature from WM. In particular, the work documented in Chapter 4 investigated how WM activation is modulated by means of an instruction to forget. In this study, we found that a cue to forget an earlier memorized object reduced attentional capture by a subsequently presented distractor that matched the earlier memorized object. In addition, we found that this capture effect was not modulated by the duration of the interval between the cue to forget and the visual search task. These findings suggest that people are able to intentionally forget a single object held in WM and that such forgetting leads to rapid but incomplete deactivation of the representation of this object. In contrary, in the study reported in Chapter 5, we found that attention was directed towards distractors that shared their color with an item held in WM regardless of whether this color had to be remembered or whether it could be forgotten. These findings imply that people cannot selectively remember just one of the features of an object held in WM, thus supporting the notion that forgetting in WM is object-based (Gajewski & Brockmole, 2006). To sum up, the current results suggest that instruction to forget leads to incomplete deactivation of the representation of a single object held in WM, whereas instruction to remember one of the features of the object held in WM does not result in deactivation of the no longer relevant feature.

Taken together, the studies presented in this thesis provide evidence for the dynamic fluctuation of WM activation in response to different task demands. In the following subsections, I will further discuss the broader theoretical implications of these findings.

What is voluntary about involuntary attentional capture?

Taken together, the studies reported in this thesis present several examples wherein information activated in WM was shown to result in attentional capture by newly presented stimuli that matched the contents of WM. An important question is whether this phenomenon of memory-driven attentional capture is automatic or at least to some extent voluntary. On the one hand, it has been shown that attention is directed toward irrelevant items matching WM content even when this always harms performance (Mannan, Kennard, Potter, Pan, & Soto, 2010; Soto & Humphreys, 2008; Soto, Humphreys, & Heinke, 2006). This suggests that memory-driven attentional capture is an automatic effect that occurs involuntarily. Alternatively, it could also be argued that memory-driven capture may arise as a result of a strategy of refreshing the memory trace in WM by resampling corresponding information from the environment.

The data presented in this thesis present several findings that appear inconsistent with a resampling account. Specifically, in the study reported in Chapter 2, we found that attention was drawn to pictures matching earlier-processed words even when participants were not informed that memory for those words would be tested at the end of the experiment, and, thus, they did not have a reason to refresh memory activation by attending to the matching picture. Moreover, the results documented in Chapter 3 suggest that the residual WM activation that results from deep encoding of a word may be as potent as goal-driven WM activation in biasing attentional selection. This again opposes the refreshing account as this account would seem to predict that participants would more often direct their attention toward pictures depicting the words that have to be remembered than towards pictures depicting the words that do not have to be remembered. Furthermore, in the study presented in Chapter 4, we found that attention was shifted to a distractor matching a to-be-forgotten object even when we never tested participant's memory for the objects they were instructed to forget. Lastly, the results reported in Chapter 5 also seem to speak against the hypothesis that attention is strategically allocated to a WM-matching distractor to improve memory. In this study, the most beneficial strategy would be to forget the no-longer relevant color as this would decrease the likelihood of interference from this feature in the memory test (Oberauer, 2001). However, we found that an instruction to remember only the shape of an object did not eliminate attentional capture by the no-longer relevant color of that object.

Taken together, despite the lack of the prospective benefits for memory performance, we found that attention was deployed to distractors that matched the contents of WM (Chapter 2, Chapter 4, Chapter 5), which could be taken as an argument against the assumption that voluntary memory resampling underlies or at least contributes to the memory-driven capture effect. Instead, the current findings are consistent with an account that assumes that the activation of information in WM automatically results in attentional selection of matching inputs from the environment (Desimone & Duncan, 1995; Soto, Hodsoll, Rotshtein, & Humphreys, 2008).

Guidance of attention by WM without active goal-driven maintenance

The work documented in this thesis presents several findings showing that recently processed items can guide visual attention even when there is no requirement to hold these items in memory. This is in contrast to a key assumption of many studies on memory-driven attentional capture, according to which, this effect depends on the active, goal-driven maintenance of representations in WM (Kiyonaga & Egner, 2013; Olivers et al., 2006). For instance, Olivers et al. (2006) found no evidence of memory-driven attentional capture by a matching item in a search display when memory for this item was tested prior the search task. This finding suggests that the representation of an item that was recently held in WM cannot guide attention when goal-driven maintenance of this item is no longer required, thus arguing against the possibility that residual activations can bias visual attention. However, it is important to note that this finding may be explained by deactivation of the representation of the item in WM when the recognition task was executed. Such a deactivation may be due to interference caused by the processing demands associated with the recognition task in which the memory item had to be selected among three alternatives. This interpretation is supported by the results presented in Chapter 2 and Chapter 3 that showed that pictures of words that had undergone deep encoding attracted visual attention, but only when there was no concurrent task that has to be executed after processing the word, thus suggesting that residual activation of the word is overwritten by encoding new items (Chapter 2) or by performing simple arithmetic task (Chapter 3).

Other studies also seem to suggest that only active maintenance of an item in WM can lead to memory-driven capture effect. For example, it has been demonstrated that when participants are presented with an object without any requirement to hold it in memory, a matching item will not attract visual attention in a subsequent task (Soto et al., 2005). In explaining the findings by Soto et al., it is important to note that the results collected in this thesis suggest that initial activation of the item in WM is mandatory to observe memory-driven capture without active, goal-driven maintenance (see also Pashler & Shiu, 1999; Soto & Humphreys, 2007). In particular, the results of the studies described in Chapter 2 and Chapter 3 suggest that requirement to judge the semantic property of a word leads to residual WM activation that in turn influences the allocation of visual attention even when the word does not have to be held in WM. Likewise, in the work presented in Chapter 4, we found that an instruction to forget a single object held in WM led to a reduction but not an elimination of attentional capture by items matching to-be-forgotten representation. Although the lack of initial activation of the item in WM can explain the lack of capture in the study by Soto et al., (2005), it does not explain why the capture effect did not occur in a study reported by Kumar et al. (2009). Specifically, in this study, Kumar et al. compared a condition in which participants were asked to hold an object in WM for a later test with a priming condition in which participants were asked to compare two objects presented one after another and to withhold their response to the search display whenever the second object differed in either color or shape from the first object. The behavioral and electrophysiological results provided evidence for a WM-bias of visual search in the memory condition but not in the priming condition. The lack of capture in the priming condition is surprising, given that the comparison task would appear to require the activation of the to-be-compared object in WM. Future studies should examine the role of WM in the comparison task that was used by Kumar et al. to shed some light on why this task does not lead to a capture effect.

Taken together, the results presented in this thesis present clear evidence that residual WM activation can lead to attentional capture by matching stimuli in the environment, and they thus demonstrate that active, goal-driven maintenance is not required for capture to occur. Importantly, however, it does seem to be the case that capture by residual activation can only occur when initial activation of the item in WM is required and when such activation is not disrupted by the requirement to process another task.

To forget or not to forget: the fate of no-longer relevant information

In the work presented in this thesis, we used the memory-driven capture paradigm to monitor the waxing and waning of WM activation due to different task requirements.

This method is a highly useful tool because testing WM activation is not limited to a few trials per participant as would be the case when an explicit measure of incidental recall or recognition is used to probe the memory representation of a previously encountered object. Specifically, previous studies showed that including even a small amount of trials on which participant's memory is probed for items that they were instructed to forget leads participants to ignore the instruction to forget (Williams & Woodman, 2012), and thus explicit testing can only be done on a few trials per participant (Williams, Hong, Kang, Carlisle, & Woodman, 2013). In the current thesis, the memory-driven capture paradigm enabled us to provide a more powerful test of whether a single object held in WM can be intentionally forgotten (Chapter 4) and how the requirement for selective remembering of a particular feature of an object influence WM activation for the other features of this object (Chapter 5). The results presented in this thesis provide evidence for the existence of an active removal mechanism that can operate in the absence of the interference from competing to-be-remembered information. Specifically, the study reported in Chapter 4 tested people's ability to forget a single object held in WM, and the results showed that an instruction to forget an earlier memorized object led to a reduction in the capture effect. Given that this reduction in attentional capture occurred in the absence of concurrent to-be-maintained information, this finding suggests that people can choose to deactivate a representation of a single object in WM, thus offering support for the proposed existence of an active removal mechanism (Oberauer & Lin, 2017). According to this model, no-longer relevant representations are removed by Hebbian antilearning which attenuates the association between an item and a context marker. Importantly, however, the capture effect was not completely abolished after an instruction to forget, which means that some activation persisted even after the instruction to forget. In this regard, our findings differ from those of previous studies that provided evidence for complete forgetting when people are cued to remember one of two items currently held in WM (Olivers et al., 2006; Williams et al., 2013). In light of these findings, it appears to be the case that the presence of concurrent to-be-remembered representation can facilitate forgetting of no-longer relevant information in WM. Interpreted in terms of Oberauer's proposal that forgetting occurs by unbinding a representation in WM from its context (Oberauer & Lin, 2017), this set of findings may be taken to suggest that shifting the focus of attention to a to-be-remembered representation will amplify the connection weights for the to-be-remembered representation which in turn further undermines the association between the to-be-forgotten item and the context that this item it is bound to.

The Hebbian antilearning mechanism that underlies unbinding in Oberauer and Lin's model (2017) is also of relevance to understanding the results obtained in Chapter 5, which show that an instruction to remember only the shape of an object stored in WM did not eliminate or reduce attentional capture by the no-longer relevant color of this object. This finding suggests that the no-longer relevant color was not forgotten and not even partially deactivated. Assuming that removing a no-longer relevant representation from WM is accomplished by unbinding the item from its context, the attenuation of the association between the item and the context would be inadvisable if one of the features of this item has to be held in memory. Taken together, the results reported in Chapters 4 and 5 provide support for the existence of an active removal mechanism that can be used to deactivate a representation of an object in WM as they suggest that such deactivation can be observed in the absence of the interference from competing to-be-remembered material (Chapter 4). Furthermore, the current results imply that forgetting in WM is object-based.

Regarding intentional forgetting of no-longer relevant information, an intriguing finding in the study reported in Chapter 4 is that the ISI between a cue to forget an earlier remembered item and the subsequent search task did not influence attentional capture by distractors matching the to-be-forgotten item. Therefore, we found no evidence for a deterioration of to-be-forgotten representations over time. This speaks strongly against decay theories which assume that information that is not actively maintained decays over time (Barrouillet & Camos, 2012; Barrouillet et al., 2004). The role of time in the forgetting of information in WM is also incorporated in the temporal distinctiveness theories (Oberauer & Lewandowsky, 2008; Souza & Oberauer, 2014). Specifically, these theories propose that forgetting depends on the amount of time between the two events. That is, temporal distinctiveness between the two potentially interfering events (e.g. requirement to remember two successive pieces of information) decreases when the time interval between these events increases, which increases the likelihood of forgetting. Note, however, that the results presented in Chapter 4 do not oppose temporal distinctiveness theories as according to these theories the lower temporal distinctiveness increases the likelihood of forgetting because it increases the degree of interference between two events. However, forgetting in Chapter 4 was tested for a single item held in WM, thus in the absence of any interfering to-be-remembered information.

To summarize, the finding that attentional capture is rapidly reduced following a cue to forget a single object held in WM suggests that people can intentionally deactivate a single item held in WM and thus provide evidence for an active removal mechanism that can operate rapidly (Chapter 4). In addition, the finding that a retro-cue to remember only the shape of an earlier memorized, colored shape did not lead to reduced attentional capture for items matching the color of this object provides evidence for the notion that forgetting in WM is object-based (Chapter 5).

Dynamic states in working memory

The studies documented in this thesis provide findings that can be understood in the context of the state-based models which assume that the representation of information in WM can be described in terms of different states of activation, which fluctuate due to attentional prioritization (Cowan, 2011; Oberauer, 2002, 2013; Olivers, Peters, Houtkamp, & Roelfsema, 2011). Specifically, a central assumption of these accounts is that attention can modulate the activation of representations in WM, such that the information that is currently relevant is assumed to be prioritized by the focus of attention whereas information that is currently irrelevant may still be maintained in WM but in a more latent state (Larocque, Lewis-Peacock, & Postle, 2014; Lepsien & Nobre, 2007; Lewis-Peacock & Postle, 2012; Myers, Stokes, & Nobre, 2017; Wolff, Jochim, Akyurek, & Stokes, 2017). The representation that is in the focus of attention is thought to exert the strongest influence on visual attention (Olivers et al., 2011).

In the studies presented in Chapter 2 and Chapter 3 we found that when people were asked to judge the semantic property of a word, attention was guided toward the picture depicting the referent of this word in a subsequent visual task. This capture effect was eliminated when an additional task had to be performed after judging the word, whereas capture occurred despite the presence of the intermediate task when the word had to be remembered. The magnitude of the capture was the same regardless of whether the capture resulted from a deep encoding of a word or from goal-driven maintenance of a word. Interpreted according to the state-based accounts of WM, a possible explanation of these results could be that the words that have to be remembered were maintained in the focus of attention state, while the words that were deeply encoded without a need to remember them were maintained in the more latent state which could be conceptualized as accessory state (Olivers et al., 2011), state of direct access (Oberauer, 2002) or activated part of long-term memory (Cowan, 2011). The words maintained in the focus of attention state are protected from the interference from an additional task, whereas words maintained in the more latent state can be overwritten by the requirement to process additional task. Interestingly, the results presented in Chapter 3 also suggest that representations of words in an accessory state are as potent in guiding visual attention as representations in the focus of attention state. In the study presented in Chapter 4, we found a reduction in attentional capture by WM matching object when this object was followed by the instruction to forget, thus suggesting that this item was deactivated. These finding could be explained by a transition of WM representation of the object from an active focus of attention state to a more latent accessory state, in which it has limited influence on visual attention.

Taken together the data presented in this thesis provide evidence for a dynamic fluctuation in WM activations that arise from different task requirements such as the type of encoding (Chapter 2, Chapter 3), processing of an additional task (Chapter 2, Chapter 3) or intentional forgetting (Chapter 4). These data can be easily accommodated by state-based models recognizing different states of WM activation that are flexibly adjusted to the current task demands.