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Commentary

Why should working memory be related to incidentally learned sequence structures?

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Janacsek and Nemeth (2013) gave a profound review about a central but poorly understood relationship: working memory (WM) and implicit sequence learning. They conclude that WM should be related to explicit (intentional) rather than implicit (incidental) sequence learning. Here, we aim to briefly extent their review regarding two important aspects when the relation between WM and implicit sequence learning is investigated and discussed: (i) the functional distinction of WM and (ii) recent evidence for an implicit WM. WM is a construct most often related to explicit (intentional, conscious) information processing (Baars & Franklin, 2003). One reason for a relation to implicit learning is that the latter is based on task representations held in WM (cf. Oberauer, Souza, Druey, & Gade, 2013, for the concept of procedural WM). According to this view, implicit sequence learning is a by-product of how people conceptualize and perform a task that contains a hidden sequential structure (Abrahamse, Jiménez, Verwey, & Clegg, 2010; Gaschler, Frensch, Cohen, & Wenke, 2012). These studies suggest, that people have a surprising flexibility in representing a task (e.g., based on spatial, colour, or verbal markers) which in turn influences the content of sequence knowledge being acquired (e.g., a spatial or a colour sequence). This flexibility likely moderates the connection to WM capacity. If, for instance, participants place high weight on visual rather than verbal representations when conceptualizing and performing the task, than visuo-spatial WM capacity should be more highly related to sequence learning than verbal WM capacity and vice versa. This might, at least in part, explain why the findings for the relationship between implicit sequence learning and WM are far less consistent than the ones on explicit sequence learning. In implicit sequence learning, most studies do not control how people represent a task, so that the WM test (e.g., verbal or visuo-spatial) might not match.

Lack of process pureness can also contribute to a relation between WM and results from implicit sequence learning tasks. Some parts of a sequence structure can become conscious, and subject to controlled processing (cf. Wessel, Haider, & Rose, 2012). A typical measure of implicit sequence learning is the reaction time difference between the practiced and a novel sequence. Independently of whether deterministic or probabilistic sequence structures are learned (e.g., Kaufman et al., 2010; Unsworth & Engle, 2005), many studies cannot find a relation of this difference score with WM capacity. One of the problems in this context is how WM is defined and measured. Based on the WM view of Baddeley and Hitch (1974), Daneman and Carpenter (1980) constructed a WM capacity task which made it possible to measure interindividual differences in how much information can be maintained in the correct order, while the attentional focus is

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recruited to processing similar or other information, so called complex span paradigms (e.g., in the operation span paradigm alternating letter/words have to be maintained and calculations be solved, ‘B’ — ‘5 − 3 = 3?’ — ‘H’ — ‘5 + 4 = 9?’ — ‘E’ — ‘3 + 1 = 5?’; e.g., Engle, Cantor, & Carullo, 1992). However, apart from “holding and processing” other potential WM (and executive) functions seem relevant like (1) relational integration (Oberauer, Süß, Wilhelm, & Wittmann, 2003, 2008; Fig. 1A), (2) scope of attention (e.g., Cowan, Fristoe, Elliott, Brunner, & Saults, 2006), (3) WM updating of old information with new one, (4) switching between task-sets, and (5) inhibition of prepotent responses (e.g., Friedman et al., 2006). Therefore, WM should be regarded as set of different processes which are temporally recruited for online information processing in the service of cognition (Cowan et al., 2005). In line with this view, studies found a relation between WM processes and implicit learning of deterministic second-order sequences (e.g., Bo, Jennett, & Seidler, 2011; Martini, Furtner, & Sachse, 2013). The results of Martini et al. (2013) indicate that the functions of relational integration and WM updating play a role in RT (reaction time) differences from the switch of a highly trained deterministic second-order sequence structure to a new one. This was the case when a response-to-stimulus interval (RSI) allowed for such processes to be triggered (RSI 300 msec condition) while no relation was found when new stimuli immediately followed upon responses (RSI 0 msec condition). A free generation task after the SRT (serial reaction time) task indicated that under both RSI conditions the

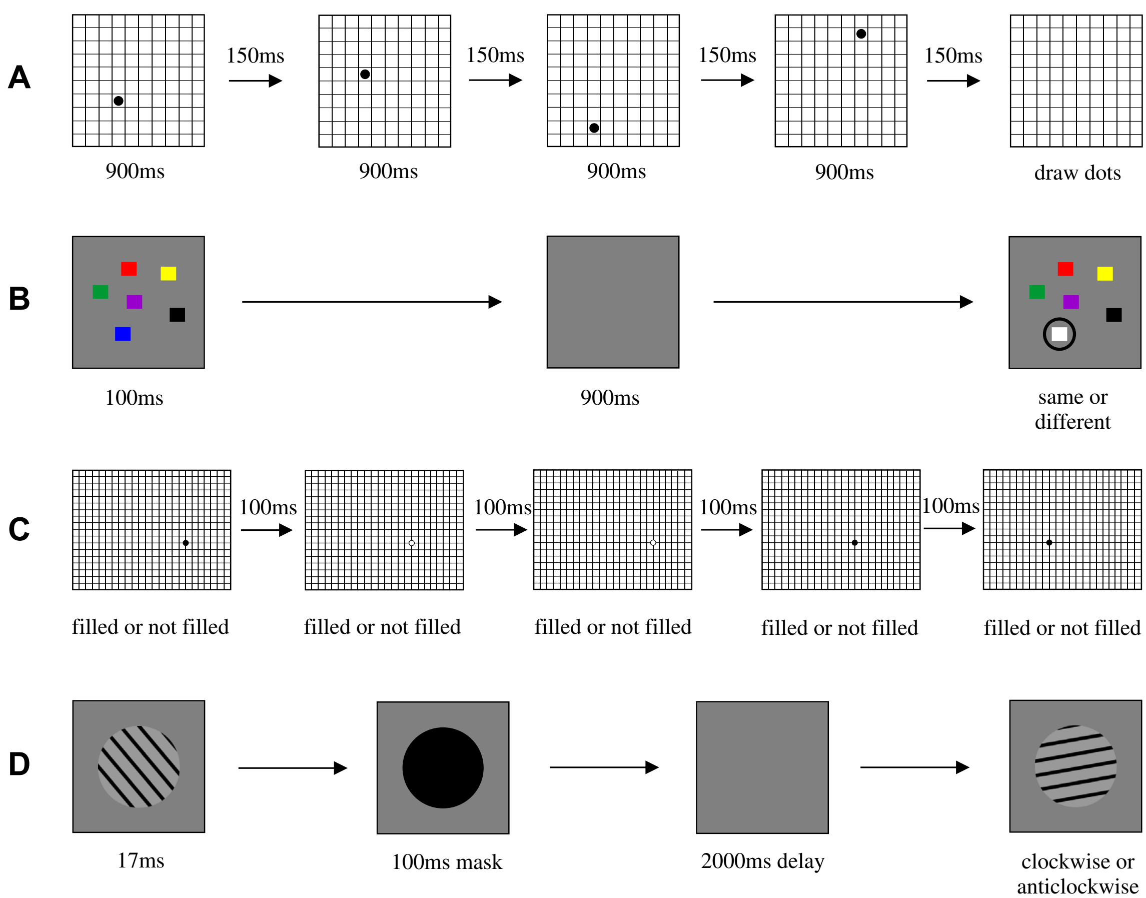

Fig. 1 — Two explicit WM tasks (A and B) and two implicit WM tasks (C and D). (A) Spatial short-term memory task measuring relational integration abilities. Dots appear sequentially in a grid consisting of a large amount of cells. Participants are required to maintain (the pattern of) the stimulus locations. After several trials participants are required to draw the dots in an empty grid. (B) Change detection paradigm measuring attentional scope. A varying number of coloured squares appear on the screen. Participants are required to hold the coloured square location associations in mind. A decision task follows stimuli presentation after a specific inter-stimulus interval. In this decision task participants have to indicate if the encircled square has the same or a different colour with respect to the colour of the square at this position presented before. (C) Filled and non-filled dots appear sequentially in a grid on the screen. In every single trial participants have to indicate if the dot was filled or not. Participants do not know whether a pattern exists behind the appearing sequence of stimuli. RTs regarding the last, fifth, trial is of critical importance. Based on the pattern sequence of the previous four dots participants RTs on response to the fifth dot in the pattern condition should decline over time. (D) A Gabor cue with a specific tilt is subliminally presented and masked. After a varying delay an explicit but rotated Gabor cue is presented. Participants have to indicate (if necessary guess) whether the actual cue is clockwise or anticlockwise rotated relative to the subliminal cue.

sequence structure was partly explicit and therefore under cognitive control. However, only under the RSI 300 msec condition relations between WM capacity and generation scores were significant. Additionally, measuring WM capacity with the change detection paradigm (Fig. 1B), a task that can be defined as measure of the attentional scope (Cowan et al., 2006; Shipstead, Redick, Hicks, & Engle, 2012), Bo et al. (2011) found that visuo-spatial WM capacity predicted implicit learning in delineation of visuo-spatial short-term memory capacity. These studies suggest that interindividual differences in some subcomponents of WM capacity indeed seem to be relevant for implicit sequence learning outcomes in tasks that match in material and temporal structure.

Finally, the issue of qualitative versus quantitative differences between implicit and explicit sequence learning has implications for the interpretation of findings reporting a relation between sequence learning and WM capacity or a lack thereof. One position is that implicit sequence learning uses the same neural and cognitive resources as explicit sequence learning – though to a lesser extent and with a higher amount of interindividual differences in task representation (see above). Thus, measurement problems might contribute to the fact that the relation of WM capacity and implicit sequence learning seems to be less robust as compared to explicit sequence learning. Prominent work on the representation of sequential structure in WM (e.g., Botvinick & Plaut, 2006; Cumming, Page, & Norris, 2003; Hebb, 1961) makes use of incidental tasks, in which sequences are encoded and retrieved as a by-product of instructed task processing. This suggests that neural and cognitive processes responsible for sequential structure in explicit and implicit cognition might overlap (see Discussion in Schuck, Gaschler, Keisler, & Frensch, 2012). In line with this, Aizenstein et al. (2004) found activity in prefrontal cortex, striatal, anterior cingulate cortex, and visual regions (V1, V2, and V3) during implicit and explicit learning conditions. Especially during explicit learning conditions they found increased activity in prefrontal cortex and anterior cingulate cortex during erroneous responses. Aizenstein et al. (2004) assume that explicit and implicit learning show overlapping but partially distinct processes. Additionally, Rose, Haider, Weiller, and Büchel (2002) argue that the ventral perirhinal cortex within the medial temporal lobe seem to have a specific role in implicitly learning the sequential pattern behind sequential regularities, whereas the basal ganglia were activated when fixed stimulus–response associations were learned, assuming that the functional roles of the brain structures depend on the learned material and not necessarily whether the sequence structure is explicit or implicit). Computational models of sequential (routine) behaviour (e.g., Botvinick & Plaut, 2004, 2006) indicate that a WM system is needed for the appropriate action selection and updating of hierarchical structured behaviour (Botvinick, 2008). This means that a 'working' system is needed even when learning and behaviour is implicitly represented within a correlational structure and without an explicit goal to learn something. This view is supported by neuroimaging studies. Schwarb and Schumacher (2009) found that the dorsolateral prefrontal cortex is selectively activated in spatial response selection, which represents one fundamental mechanism of sequence learning. Furthermore, Botvinick, Niv, and Barto (2009) also assume that the dorsolateral prefrontal cortex and the dorsolateral striatum act in selecting an action in hierarchical organized behaviour beside the ventral striatum and orbitofrontal cortex, which are capable of calculating a prediction error. Additionally, the anterior cingulate cortex may have a specific role in error monitoring and adaption to errors (Narayanan, Cavanagh, Frank, & Laubach, 2013; Rushworth, Noonan, Boorman, Walton, & Behrens, 2011).

Evidence for an implicitly operating WM was postulated by Hassin, Bargh, Engell, and McClullock (2009). Participants had to decide whether a sequentially appearing circle within a 24 × 18 grid is empty or full (Fig. 1C). Three task-sets were formed. In the 'pattern set', five circle locations followed a predetermined pattern; in the 'broken set', the first four circle locations followed a predefined pattern, but not the fifth circle location; in the 'control sets', the first three circle locations were randomly selected, whereas location 4 and 5 followed a pattern. RTs in the 'broken sets' were longer than the ones in the 'pattern sets', the 'control set' was somewhere in between. Across all experiments, they found no evidence for the intention to extract a pattern, or pattern-awareness, arguing for an implicit WM (Hassin, 2010; for a short-term and long-term implicit memory see Maljkovic & Nakayama, 1994, 2000; McKone, 1995; McKone & Dennis, 2000). This view is supported by Soto, Mäntylä, and Silvanto (2011) who found that their participants could subliminally encode the orientation of a (masked) Gabor cue and use this information in a following explicit discrimination task (Fig. 1D). Participants were presented with a short masked Gabor cue orientation (e.g., 40°) and had to indicate whether a following explicit presented Gabor cue (e.g., 70°) was clockwise or counterclockwise tilted relative to the previously presented subliminal stimulus. In a following awareness test participants had to indicate whether they were aware of the masked Gabor cue or not (4 point scale; from 1 = 'I did not see anything' to 4 = 'I saw the stimulus and its orientation'). Results for the '1' responses could show that correct target answers were above change level. This was found even when a masked distractor Gabor cue was implemented in a delay period (2 and 5 sec) between the mask of the first Gabor and the explicit discrimination test. A neuroimaging study of Dutta, Shah, Silvanto, and Soto (2014) found that the (rostral) prefrontal cortex supports these visual WM operations regardless of conscious awareness of the critical cues. Additionally, these results get in line with findings that can show that complex higher order cognitive abilities like reading and calculating, which were previously related to explicit, conscious information processing, can take place unconsciously, when different measures are applied (e.g., the continuous flash paradigm, which makes it possible to prolong the subliminal stimulus presentation; Sklar et al., 2012).

In summary, it may be too early to conclude that WM and its capacity limit(s) are not involved in implicit learning. It is important to focus on the match between (i) task representations held in WM during implicit sequence learning tasks and (ii) representations gauged by tests of WM capacity. This should help to link long-term memory representations of sequential structure to implicit processes responsible for sequential structure in WM.

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