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Discussion forum

The puzzle is complicated: When should working memory be related to implicit sequence learning, and when should it not? (Response to Martini et al.)

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Martini, Sachse, Furtner, and Gaschler (in press) commentary highlights two points related to the relationship between working memory (WM) and sequence learning (SL): 1) how the functional distinction of WM can affect the results when investigating this relationship, and 2) how implicit WM might have a stronger influence on implicit SL than the traditional construct of WM does.

We agree with Martini et al. (in press) that different aspects of WM can have different relations to SL. We briefly addressed this question in our paper, suggesting, for example, that a stronger relationship might be found within-domain (e.g., between *visual* short-term memory/WM and *visuospatial* SL) than between-domains (e.g., between *verbal* short-term memory/WM and *visuospatial* SL) (Janacsek & Nemeth, 2013). In addition, it is also important to consider whether SL is implicit or explicit. Studies so far have shown a stronger relationship between WM and *explicit* rather than *implicit* SL (e.g., Frensch & Miner, 1994; Unsworth & Engle, 2005; Weitz, O'Shea, Zook, & Needham, 2011). Supporting this claim, Martini, Furtner, and Sachse (2013) have demonstrated the role of relational integration and WM updating in SL under specific conditions (with longer, 300 msec response-to-stimulus intervals, RSIs). As they reported, under this condition participants gained more explicit knowledge about the hidden sequence structure than in the 0 msec RSI condition. WM capacity correlated with SL as well as with the level of explicit knowledge under the longer RSI condition, suggesting that these participants were able to use more cognitive control during SL. This result is in line with our conclusion that WM capacity is more related to *explicit* than to *implicit* SL.

Additional evidence of the functional independence of WM and *implicit* SL comes from neuropsychological studies. For instance, weaker WM performance but intact implicit SL has been found in Obstructive Sleep Apnea (OSA), showing that long-term disruption to normal sleep pattern and/or hypoxia affects WM but not implicit SL (Nemeth, Csábi, Janacsek, Varszegi, & Mari, 2012) even if partially overlapping brain networks are subserving these functions.

Martini et al. (in press) also suggested extending the investigation of this relationship to other WM and executive functions (EF) such as relational integration, scope of attention, updating, switching and inhibition. It is important to note that in our review we focused only on a narrower, more classical definition of WM where storing information for a short period of time was a crucial component beside the manipulation of information. However, changing the scope of research to the EF, relationship can be found between some EFs and *implicit* SL. In contrast to Martini et al.'s (in press) suggestion, this correlation can even be negative. For instance, in our recent paper (Nemeth, Janacsek, Polner, & Kovacs, 2013) we investigated implicit SL under hypnosis and compared it to a waking alert condition. Additionally, we measured individual differences in EF using two tasks: the semantic fluency and Wisconsin Card Sorting Tasks. We found that participants showed better SL under hypnosis compared to the alert condition, presumably, due to the disconnection between some frontal lobe areas and other brain regions during hypnosis. Moreover, individual differences in EF further detailed this relationship: in the alert condition participants with higher EF showed weaker sequence-specific learning

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than participants with lower EF; this difference, however, disappeared in the hypnosis condition because of a weaker reliance on frontal lobe functions during SL compared to the alert condition. Altogether these results suggest an inverse relationship between at least some EFs (e.g., shifting) and *implicit* SL, which might be interpreted as a competition between different but potentially overlapping fronto-striatal networks underlying these functions (Filoteo, Lauritzen, & Maddox, 2010; Janacsek, Fiser, & Nemeth, 2012; Poldrack et al., 2001; Stillman, Feldman, Wambach, Howard, & Howard, in press).

Martini et al. (in press) also highlighted that according to computational models of sequential (routine) behavior a WM system is needed for appropriate action selection and updating of hierarchical structured behavior (e.g., Botvinick, 2008), even if that behavior is based on implicit/incidental processes. We agree with this claim: it seems plausible that a local short-term storage is necessary for processing sequence information (e.g., actively maintaining and binding several items in the sequence), although the exact nature of this short-term storage and its relation to WM is still unexplored. Based on the studies we reviewed, even if such local short-term storage dedicated to SL exists, it seems unlikely to be connected to the classical concept of WM. Hassin, Bargh, Engell, and McCulloch (2009) attempted to capture a more implicit aspect of WM by specific tasks, however there is no empirical data about its relation to implicit SL yet.

Finally, it is important to keep in mind that a long-standing debate on the qualitative vs. quantitative differences between implicit and explicit SL has resulted in studies suggesting that implicit SL relies on a weaker representation compared to explicit SL (quantitative difference), making it more challenging to obtain significant results on the relationship between WM and implicit SL. Further studies need to directly address this issue since there is also a growing body of evidence showing qualitative differences between implicit and explicit SL (for the debate see Cleeremans, 2011; Cleeremans & Jiménez, 2002; Jiménez, Vaquero, & Lupiáez, 2006).

In summary, the relationship between WM and SL is quite complicated and can widely differ based on several factors. In our review paper (Janacsek & Nemeth, 2013) we attempted to move away from the traditional research approach that aims to relate WM to all cognitive functions (including SL), often leading to oversimplified conclusions about these relationships. Instead, in order to understand the neurocognitive background of these functions, we suggested to think about the relationship between WM and SL in a more sophisticated way by exploring what factors can influence this relationship, and in which cases we can find no or even negative correlation between WM and SL.

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