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Working Memory Capacity and Learning Underlying Conceptual Relationships Across Multiple Documents

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Summary: A common usage of textual repositories of information is to seek out and gather important information for a specific learning goal. However, not all material is organized in a single location, and users are often forced to visit multiple pages or sources to develop understanding. In these situations, are different learners more or less sensitive to drawing the underlying connections between multiple documents, which are relevant for the eventual learning goals? This study examines the performance of undergraduates who vary in working memory capacity as they were asked to learn about plants from a Wiki-like website. Participants were pretested on their knowledge of both biology and the plant kingdom. Results indicate that learning underlying conceptual structure is indeed predicted by working memory, but not prior knowledge. This suggests that individual characteristics should be considered when designing learning technologies in the future. Copyright © 2012 John Wiley & Sons, Ltd.

Although the internet provides access to large and rich sources of data, unfortunately this information is presented and organized in many different ways across the web, and is often scattered across several pages, links, and so on. This kind of dispersed presentation is also indicative of many learning tasks that are not necessarily online (e.g. searching out multiple sources in an encyclopedia to write a final paper). This manner of presentation requires users to visit multiple sources or documents to locate the information necessary to realize the learning goals. As such, readers must not only delve beyond the surface features of these isolated texts and extract a more coherent, deep understanding of each one (i.e. situation model; van Dijk & Kintsch, 1983 or mental model; Johnson-Laird, 1983), but must also integrate *across* texts to form an accurate understanding of the overall content. The distributed nature of such presentations thus induces an additional processing demand, namely that readers must integrate passages across links, pages, sources, and the like in order to form a complete mental representation of the material (Perfetti, Britt, & Georgi, 1995; Zwaan & Radvansky, 1998). This is especially problematic given that such diffuse presentations could potentially disrupt the overall coherence of the content, which has been shown to reduce text comprehension (McNamara, Kintsch, Butler-Songer, & Kintsch, 1996; Zwaan, Magliano, & Graesser, 1995).

Although the user is sometimes given navigational aids such as a site map or other dynamic linking structure to help organize information in a given website or repository, this is not always the case (Nilsson & Mayer, 2002). In such cases, the user must rely on what little knowledge they have of the site or document to form an *ad hoc* representation of how information is organized or presented, and, more importantly, how the material relates together conceptually (Gernsbacher, 1990). This knowledge can include elements such as the perceived structure of the material, existing domain knowledge, or even prior search strategies (Foltz, 1996; Meyer, Middlemiss, & Theodorou, 2002; O'Reilly & McNamara, 2007; Voss & Silfies, 1996). Notably, the more closely this *ad hoc* structure matches the actual structure of the source, the likelihood that the learner actually understands the material and can thus find additional novel information, also increases (Kintsch & Yarborough, 1982; Mayer, 1982; Taylor, 1982).

Thus, the successful search and navigation of any multi-document repository of information that does not contain explicit organizational cues is a direct function of the quality of the users' prior knowledge and requires that the user integrate this existing knowledge with information from the current reading activity to guide their subsequent behavior (Graesser, Singer, & Trabasso, 1994; van Dijk & Kintsch, 1983). In other words, when information is dispersed across several different websites or documents, it becomes critical for the learner to not only extract relevant information from these sources, but also be able to understand how the extracted information relates across these multiple pages in coherent ways. Cognitively, this type of integrative undertaking (e.g. combining information from the long term store and short term memory in goal-directed ways) is commonly associated with the working memory system (Baddeley, 2003; Ericsson & Kintsch, 1995). Consequently, effective use of the multiple documents to learn requires not only the interaction of several memory systems, but also lies at the intersection between prior understanding of common conventions and content, and the ability to apply such knowledge to the current experience.

Working memory and learning from text

Working memory capacity (WMC) is a stable cognitive construct that represents how well an individual can control or focus their attention, and thus maintain relevant information accessible to consciousness. (Conway et al., 2005; Cowan, 2005; Friedman & Miyake, 2004). The working memory system is responsible for processing new incoming information, using already learned information to modify thoughts and behaviors, focusing attention while completing a given task, and also remembering additional information not immediately needed to complete a current task but that might be needed later (Baddeley, 2003). In this way, it goes beyond the traditional theory of short-term memory (Daneman &

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Merikle, 1996) by including the need for executive function (Baddeley, 1996).

Working memory capacity has been used to predict performance across a wide range of tasks, such as learning science (Geiger & Litwiller, 2005; Sanchez & Wiley, 2006), learning and retrieving simple strings of letters or words from a given set (Conway & Engle, 1994), and other tasks involving higher order cognition, such as assessing fluid intelligence (Unsworth & Engle, 2005; Kane, Hambrick, & Conway, 2005).

The basic structure of the WMC includes a central executive and several sub-stores, likely organized by modality (i.e. phonological loop, visuospatial sketch pad, and episodic buffer; Baddeley, 1986; Baddeley, 2000; Baddeley & Hitch, 1974). Whether or not WMC represents a unitary attentional construct has been argued extensively in the literature, with some suggesting a distinction between verbal and visual attention (Friedman & Miyake, 2000; Miyake & Shah, 1999; Shah & Miyake, 1996). However, more recent research has demonstrated that the attentional component of WMC may in fact be unitary (Kane et al., 2004), and that previous estimations of a divergence between a verbal and visual WMC system are likely traceable to the modality specific stores rather than the executive component of WMC itself. Similarly, some also suggest that the constructs of both fluid intelligence (*Gf*) or general intelligence (*g*) and WMC are nearly synonymous (Kyllonen & Christal, 1990; Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004). Related to this point, again recent research suggests that these constructs are indeed separate (but highly correlated) and share variance due to the need to control or focus attention across these tasks (Heitz et al., 2006; Kane et al., 2005; Unsworth & Engle, 2005). Thus, WMC represents a unique and verifiable construct that exerts a domain-general influence on performance, independent of crystallized intelligence or reasoning facets.

Specific to the current study, WMC has been directly connected to several aspects of text comprehension. For example, WMC has been connected on a very general level to performance on standardized verbal tests (e.g. Verbal SAT; Daneman & Carpenter, 1980; Engle, Nations, & Cantor, 1990) and the formation of situation models (Friedman & Miyake, 2000; Haenggi, Kintsch, & Gernsbacher, 1995). WMC has also been related to the generation of bridging inferences (Daneman & Carpenter, 1983; Singer, Andrusiak, Reisdorf, & Black, 1992; Singer & Ritchot, 1996), sentence comprehension (Jefferies, Lambon-Ralph, & Baddeley, 2004), and using contextual information to generate word meanings (Daneman & Green, 1986). This relationship between WMC and text comprehension has also been connected to reading behavior in children (Cain, Oakhill, & Bryant, 2004), as lower WMC readers have more difficulty resolving textual anomalies (Yuill, Oakhill, & Parkin, 1989), and also suffer other comprehension difficulties likely as a result of a breakdown in inhibitory processes (Chiappe, Hasher, & Siegel, 2000; De Beni & Palladino, 2000).

The aforementioned studies all suggest that WMC is integral for the connection of relevant information within a given text(s). As learning from multiple documents requires the appropriate integration of information from long and short-term memory to guide the search for understanding (Cook, Halleran, & O'Brien, 1998; Masson & Miller, 1983; Pazzaglia, Toso, & Cacciamani, 2008), those higher in WMC should be better able to grasp and formulate their understanding of the overall content by drawing appropriate inferences and relations between units within the WM subsystems. Further, as users are realistically engaging in multiple processes when using such dispersed knowledge repositories (i.e. developing and understanding a topic, while also searching for keywords, etc.), it is also likely that higher WMC individuals are better positioned to resolve this intra-task competition for mental resources. As such, high WMC individuals should be more sensitive to the implicit organization of the material, even when these underlying relationships are not obvious.

In this experiment, individuals who varied in WMC read a realistic Wiki-like website about plant taxonomy, while they also completed a secondary search task to locate answers to several simple factual questions. Participants were tested before and after reading on their understanding of the underlying hierarchical structure inherent to the domain and their basic knowledge of the domain. Importantly, this underlying structure was not conveyed explicitly through the website itself. It is hypothesized that higher WMC learners would be better able to develop a complex understanding of the material, specifically the implicit organization of the plant taxonomy. As these high WMC individuals are better able to keep relevant information in mind, and thus make supportive inferences across the texts, higher WMC individuals should be better equipped to use the information contained in these discrete textual units to form an understanding of the underlying conceptual structure of the overall content area. Similarly, as lower WMC individuals should be more taxed by the secondary search task, and thus less free to engage in this type of secondary processing, these individuals should be less likely to develop an appreciation of this underlying conceptual structure.

METHODS

Participants

Sixty-two native English speaking undergraduates (40.3% female) completed this experiment for course credit in an Introductory Psychology class at a large public university in the southwestern United States.

Materials

Text and website structure

The participants read a website on the taxonomy of plants, adapted from material on Wikipedia (Wikipedia, 2010). The site was organized in a hierarchical tree structure that contained four levels (Figure 1), with the higher levels including the broadest classes of plants (e.g. vascular and non-vascular), and becoming more specific as one moves down the tree to include specific species (e.g. conifer, Marchantiales, etc.). Overall, the text contained 11 810 words (spread over 24 separate pages), with each page on the website containing an average of 492 words relative to a specific part of the plant taxonomy. This text also contained no images, and the participants navigated the website through provided links alone. The participants could

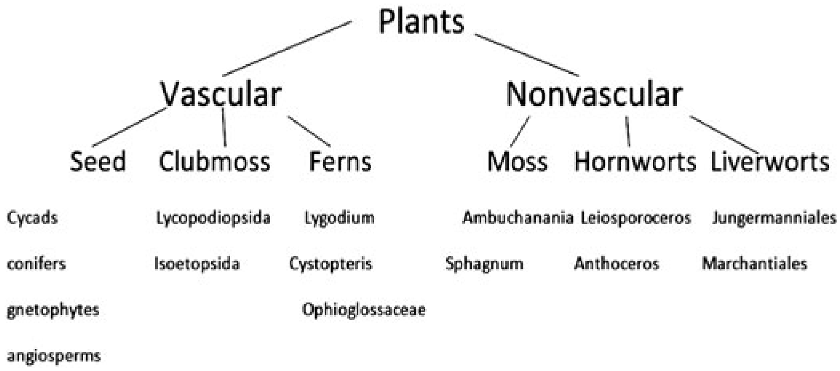

Figure 1. Website structure

only navigate one link either up or down the tree and, thus, were not allowed to skip at random around the structure or move sideways among units at a given level. For example, if the participants were in the 'Seeds' sub-topic (Figure 1) and wanted to then read about 'Clubmoss' or 'Ferns', they would be first required to navigate back up to the 'Vascular' level, and then into either of these categories. As such, users were not able to move laterally within the tree using a single link, thus minimizing the chance of confusion while also implicitly suggesting an overall hierarchy. Importantly, the participants were never given any explicit referent to the hierarchical organization of the site and were merely told they would be reading a website on the plant kingdom. The participants always first entered the hierarchy at the top level ('Plants') and were free to navigate through the site as they desired.

Pretest

Prior to reading, a pretest was given to assess the participants' prior knowledge of plants. The pretest asked the participants to rate their knowledge of Biology and Plants on a 1–5 scale (1 being lowest). The pretest also contained a hierarchical tree construction task and matching terms task. In the tree construction task, the participants were given the eight terms that occupy the first three levels of the tree, and asked to correctly place the terms into the appropriate locations on the tree. The participants were awarded a single point for every correct placement in the tree. For the matching terms task, there were four questions. Each question gave the participant an item in the plant hierarchy of the website and then a list of five other items in the hierarchy. The participant then was instructed to circle the two items that appear beneath the given item in terms of plant hierarchy. The participants were awarded a single point for every correct item that was circled, for a maximum of eight possible points. It is hypothesized that the matching task measures the participants' ability to detect simple explicit relationships between sub-units and a provided referent, whereas the tree construction task requires the participants to go one step beyond this and generate the hierarchy completely from memory (e.g. the referent and the subsequent units). Thus, the tree construction task is considered a measure of more deep understanding of the material and inherent relationships between concepts.

Search questions

While reading through the website, the participants were asked to also complete 18 search questions about the content area. The search questions were simple factual questions and were drawn evenly from the entire website. The inclusion of these search questions was designed to provide a more authentic medium for examining subsequent performance changes, as the participants are often engaged in multiple processes when interacting with learning materials.

Post-test

At the end of the experiment, the participants completed a reordered version of the tree construction and matching tasks to assess any gains in understanding of site material. Single points were again awarded for every correct placement or matched term.

Working memory measure

All participants completed the Automated Operation Span task (AOSpan) to evaluate their WMC (Unsworth, Heitz, Schrock, & Engle, 2005). In the AOSpan task, the participants are shown a simple equation followed by a letter (e.g. IS (8/4)− 1 = 1? C), and asked to evaluate the correctness of the equation while remembering the letter for a later test. Equation-letter strings were presented in sets that contained between two to seven strings. The participants completed three trials of each set size, and the order of these sets was randomized. The participants were awarded a single point for every correct letter recalled. Importantly, in order for a response to be considered correct, the correct letter must be recalled in the correct serial position. All other administration and scoring followed the recommendations of Unsworth et al. (2005).

Procedure

The participants were first given 10 minutes to complete the pretest. After completing the pretest, the participants were then given the search questions and directed to the website. The participants were given 25 minutes to search through the site and answer as many of the search questions as possible, as correctly as possible. After the 25 minutes were up, the participants then completed the post-test, which took approximately 10 minutes. The participants were then debriefed and dismissed. The entire experiment took no longer than 1 hour. The participants completed the WMC measure in a separate half-hour session.

RESULTS

Search questions

Overall, the participants were able to adequately complete the search task ($M = 9.93$, $SD = 3.73$). Importantly, performance on the factual search questions was not significantly correlated with WMC ($r(61) = .04$, $p > .05$), nor reported knowledge of plants ($r(61) = .07$, $p > .05$), or biology ($r(61) = .08$, $p > .05$). Further, this was also not significantly correlated with initial performance on either the hierarchical tree ($r(61) = .24$, $p > .05$) or matching terms ($r(61) = .17$, $p > .05$) pretests. This suggests that the search questions were more or less of equal difficulty for all individuals, regardless of their WMC or prior knowledge.

Differences in matching task

The participants did significantly improve in their ability to match appropriate terms after reading the website from pre ($M = 3.18$, $SD = 1.79$) to post ($M = 5.00$, $SD = 1.93$; $F(1, 61) = 34.99$, $\eta_p^2 = .37$, $p < .01$). In order to examine the influence of WMC on learning the underlying structure of the website, a hierarchical linear regression was conducted on the pre–post difference scores for the matching task. WMC, knowledge of plants, knowledge of biology, and the number of search questions correctly answered were entered into the first block of the analysis, and then interaction terms between WMC and the remaining three variables were entered into the second block.

Results indicated that the improvement in the matching task was not explicitly connected to either WMC, prior knowledge, or performance on the search questions ($R^2 = .09$, $F(4, 57) = 1.37$, $p > .05$). The addition of the interaction terms in the second block also failed to significantly improve the overall model (R^2 change = .06, $p > .05$). This suggests that WMC, prior knowledge, or correctly answered search questions do not significantly predict the gain of simple explicit relational knowledge.

Differences in tree construction task

The participants did also significantly improve in their understanding of the hierarchical structure of the website from pre ($M = 3.39$, $SD = 2.49$) to post ($M = 5.68$, $SD = 2.24$; $F(1, 61) = 36.15$, $\eta_p^2 = .37$, $p < .01$). In order to examine the influence of WMC on learning the underlying structure of the website, a hierarchical linear regression was again conducted on the pre–post difference scores for the hierarchical tree construction task. WMC, knowledge of plants, knowledge of biology, and the number of correctly answered search questions were again entered into the first block of the analysis, and then interaction terms between WMC and each remaining variable were entered into the second block.

The results of the first block of the analysis show that the overall model did predict a significant portion of the variance in gain on the tree construction task ($R^2 = .18$, $F(4, 57)=3.10$, $p<.05$), and only WMC was a significant predictor of this gain ($\beta=.34$, $p<.05$; Figure 2). Prior knowledge of plants ($\beta=.21$), biology ($\beta=-.25$), or the number of search questions correct ($\beta=.14$) did not significantly predict differences in the tree construction task ($p>.05$). Further, the addition of the interaction terms in the second block of analysis did not significantly improve the fit of the model (R^2 change=.00, $p>.05$).

Thus, these results suggest that while WMC, prior knowledge, and search performance were not predictive of understanding simple relationships among knowledge units gained through reading a wiki-like site, only WMC was predictive of the gain in understanding the underlying structure of the site. It is likely that those higher in WMC were better able to learn this material given their enhanced ability to hold and integrate relevant (but not explicit) information in mind, while also completing the search questions. Importantly, this gain was not connected to prior knowledge of the domain, or performance on the search questions themselves.

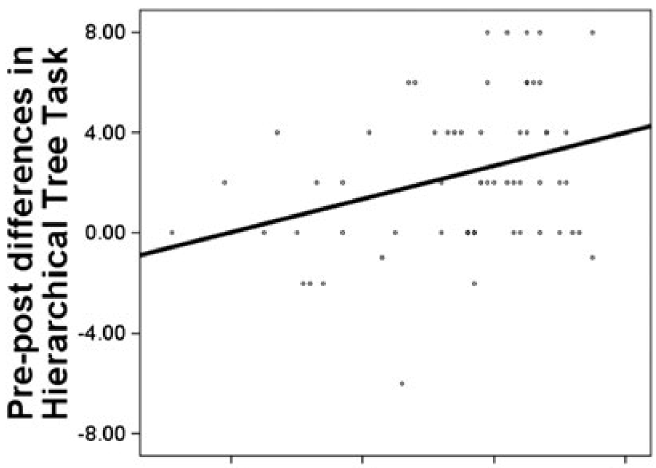

Figure 2. Relationship between working memory capacity (WMC) and difference in performance on Hierarchical Tree Task. Positive differences represent better performance on the post-test, and negative differences equal better performance on the pre-test. No difference equals equivalent performance across administrations

DISCUSSION

The results of this study suggest that WMC does influence how well individuals learn and remember the underlying, non-explicit, structure of complex material. Although WMC was not related to the ability to learn simple explicit relationships, those learners who were higher in WMC improved in their implicit understanding of the relationships underlying the material, whereas those lower in WMC did not. Importantly, this effect was not mediated by either prior knowledge of the material, as indicated by the non-significant interaction between WMC and prior knowledge measures, or how well they searched the site (i.e. search question performance).

This suggests that higher WMC individuals, likely due to their ability to focus their executive functions to attend to and connect said information more appropriately across the multiple texts, gain a greater appreciation of the underlying implicit relationships across such a diffuse presentation. As such, they are in fact more sensitive to underlying relationships between units. This is consistent with previous research that found a similar effect for high WMC individuals when completing a problem-solving task (Reber & Kotovsky, 1997), and numerous studies that have suggested that higher WMC individuals are more likely to connect information across portions of text (Chiappe, Hasher, & Siegel, 2000; Daneman & Green, 1986; Masson & Miller, 1983; Singer et al., 1992; Yuill et al., 1989). Further, this also suggests that at least part of the advantage usually demonstrated by higher WMC individuals when reading a text may in fact be a more tacit understanding of underlying principles or relationships that are not necessarily explicitly stated. In other words, while low WMC individuals might be just as adept at processing local connections within a text as high WMC individuals, these results suggest that they might instead struggle with forming more global connections that provide a framework for understanding said local relationships. This type of deep inferential understanding and connection of conceptual units lies at the crux of what is commonly referred to as the 'situation model' in the text processing literature, whereas the relationships between units are key, and not necessarily the more superficial surface features of the text (Graesser et al., 1994; van Dijk & Kintsch, 1983).

It is worth considering other explanations for this effect. For example, could it be that high WMC readers just read faster and thus are more likely to have time to devote to the formation of this interconnected structure? Or are high WMC readers more adept at making local connections within the material, or perhaps using the pretest as a conceptual prime, either of which would translate into a higher likelihood of recognizing the larger more global relationships? Conversely, is it that low WMC readers instead just struggled with the requirement to complete the search questions while reading? While these explanations are all plausible, it seems unlikely that the current pattern of results is connected to either the reading speed, requirement to answer search questions, or the local processing/priming explanations.

The main piece of evidence that speaks against the reading speed explanation is the lack of significant finding relating search question performance to either tree or matching performance. Given the length of the site, one of the main limitations on successful performance of the search questions was how completely individuals were able to explore the entire hierarchy to find the answer. As individuals were highly accurate on their search question responses (>90% on average), the scores on the search responses likely reflect time pressure to read and locate information throughout the text. If high WMC individuals simply read faster, one would also naturally expect a higher performance rate on the search questions. This would then also serve as a proxy for time remaining to focus on the conceptual relationships across texts, and thus should likewise be related to the tree or matching task, which again are considered measures of more global and proximal conceptual connections. In other words, the faster one answers the search questions, the more time one should have to make the connections across the texts, either proximal or distal. Given that search questions alone did not predict changes in either matching or tree construction performance (and also did not interact with WMC to influence either), this explanation seems less plausible.

This also speaks directly to the issue of whether answering the search questions unduly handicapped the low WMC individuals. Again, given that the number of search questions answered did not predict performance alone, or interact with WMC, one must conclude that the search question requirement was not predictive of performance in either WMC group. If the search questions were negatively affecting one WMC group above-and-beyond the other, one would anticipate such an interaction to moderate performance, however this was not observed.

Further, the lack of a relationship between WMC and the matching task also seems to suggest that all readers were able to connect proximal pieces of information (e.g. 1-link away); however, low WMC readers were less able to make more global connections, as evidenced by the tree construction task. This again suggests that high WMC individuals are better able to infer more general patterns or meanings while reading, consistent with prior research (Singer et al., 1992; Trabasso & Suh, 1993; Yuill et al., 1989). Further, if high WMC individuals were just using the pretest as a kind of advance organizer (AO) to structure their knowledge globally, one would likewise expect a facilitation within both their local and global connections, and perhaps also in their search question performance (similar to the logic of the reading speed explanation). However, these patterns were not observed, and there was only a relationship between WMC and performance on the tree-construction task. Further, research on AOs (which are essentially conceptual primes given before reading) would suggest the exact opposite: low-ability individuals should in fact benefit *more* than high ability individuals from such priming (if it was occurring), as it offloads some processing demands from these low-ability individuals (Stone, 1983). Obviously, this reverse pattern was also not the case and makes this priming explanation even more unlikely. Instead, the pattern of results suggests that high and low WMC individuals were very similar in their reading activity, and thus their ability to connect proximal pieces of information; however, only high WMC individuals were able to make the larger, more global cross-textual connections across the existing information.

These results are particularly important for designers of online learning environments, as it suggests that individual differences do indeed moderate how participants grasp critical information that is often-times not conveyed explicitly. These results suggest that lower WMC readers struggle with making global connections across multiple texts, and efforts to make such connections more explicit might prove useful in equating learning across individual differences. This would align with prior work that has suggested that adding such features (i.e. topic sentences; Budd, Whitney, & Turley, 1995), helps low WMC readers make more broad textual connections. Similarly, such organizational information might also help low WMC readers more appropriately refine their goals for reading when using multiple documents to actually understand the information, rather than to simply browse for facts, which naturally impacts comprehension (Linderholm & van den Broek, 2002). Future work should extend these findings to other domains and perhaps consider other individual differences that might also impact learning from multiple documents and other web searching behavior.

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