Bentley University

HF700: Foundation in Human Factors

Working Memory

Memory, Load, & Emotional Subsystems
Feat. Ultrasound Case Review

Kerry Lawlor

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Introduction

This product review explores the importance of working memory (WM), cognitive load, and emotional subsystems as they relate to the field of design. WM is the managing and holding of temporary units of information to execute cognitive tasks (A. Baddeley, 1998). Cognitive load describes a trifecta of resources consumed by working memory (Sweller, 2010). Emotional subsystems, particularly motivation and anxiety, interplay with WM and affect performance (Darke, 1988). Whereas primitive animal reasoning is responsive to singular stimuli and particularly prone to interference, evolution has supported WM by allowing humans to take stock of multiple independent pieces of information that promote learning and decision-making necessary for survival (Carruthers, 2013). WM is important to our everyday lives because it is the cognitive key bridging sensory and long-term memory (LTM) that enables us to make decisions, follow stories, remember directions, etc. For interaction design specifically, WM is a critical input for calculating workload analysis of informational displays. This paper will describe and apply the science of WM to an ultrasound case study. WM can be characterized by its limited capacity, time constrained, and highly volatile nature.

Limited Capacity

WM is the process of manipulating and temporarily storing information that is assumed required for various cognitive activities, such as decision making (A. Baddeley, 2003). Alan Baddeley and Graddham Hitch first published a model of WM in 1974 which argued that WM encompasses three subsystems that are limited in capacity and function independently of one another (A. D. Baddeley & Hitch, 1974). These three components include the phonological loop, the visual/spatial sketchpad (VSS), and the central executive (A. Baddeley, 1996). The phonological loop ("the inner ear") is responsible for storing and processing verbal and acoustic information which helps interpret spoken and written material (A. D. Baddeley, Gathercole, & Papagno, 2017). The VSS ("the inner eye") is responsible for storing and processing pictorial and spatial information which helps us navigate our environment (Pickering, 2001). Both of these subsystems are dependent upon the central executive, which is the control center of the mind as it directs attention, suppresses intruding thoughts, and coordinates multi-tasking (Morris & Jones, 1990).

The central executive is the most important component of the model as attention and data are allocated to the two subsystems at its discretion. Unlike the phonological loop and VSS which are specialized storage systems for input from the sensory memory system, the central executive controls attentional processes (A. Baddeley, 2002). It enables the WM system to pay attention to some stimuli while dismissing others, thus helping to minimize distraction (Carruthers, 2013). In addition to managing attention, the central executive is also home to key cognitive enterprises, such as metacognition (Shimamura, 2000) problem solving (Carlson, Zelazo, & Faja, 2013), or creative thinking (Carruthers, 2013).

After this three-part model failed to explain results from various experiments, it was improved upon by Baddeley and his colleagues in 2000 with the inclusion of a fourth component, the episodic buffer (A. Baddeley, 2000). The episodic buffer links WM to LTM. It temporarily manages and stores information represented as multimodal code in order to integrate information from the subsystems and LTM into a distinct episodic representation (Carruthers, 2013). The episodic buffer connects to Tulving's theory of episodic memory (Tulving, 1983), but it differs in that the episodic buffer of Baddeley's model acts as a temporary store. This integration resonates with Collins and Loftus' theory of semantic spreading because the number of increased connections that are more diverse phonologically and visuospatially will result in easier activation and retrieval of related LTMs (Collins & Loftus, 1975). The addition of the episodic buffer cemented Baddeley and Hitch's multicomponent model as the prevailing theory in the study of WM.

However, alternative theories are emerging that offer a slightly different viewpoint on the WM system. For example, whereas the multicomponent model separates WM and LTM functionally, Cowan's Embedded-Processes Model posits that a subset of the representations held in WM can also be found in an activated state of LTM and integrated in the current focus of attention (Cowan, 1999). Furthermore, Liberman challenged the VSS aspect of the multicomponent model by criticizing the assumption that spatial information was first visual input (A. D. Baddeley & Lieberman, 2017). He substantiated his claim by pointing out that blind people have never processed visual information, yet have exceptional spatial awareness (A. D. Baddeley, 2017). Therefore, he argued that the VSS should be separated into two different channels: one for visual information and one for spatial information.

George Miller's *"The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information"* is one of the most highly cited papers in psychology and argues that the number of objects someone can hold in WM is 7 ± 2 (Miller, 1956). Therefore Don Norman encourages designers to put critical "knowledge in the world" when completing fields and carrying information over from screen to screen because it alleviates some of the user's strain on WM (Norman, 2013). A novice will be on the lower end of that range, since they still need to build appropriate schemas when learning new material, while experts will be on the higher end of that spectrum since they have stronger and more efficient semantic networks easily activated in their LTM (Collins & Loftus, 1975). Because WM varies with population (e.g., WM is lower in the cognitively disabled, the elderly, etc.), this rule is not meant to be applied as an exact science. Miller also theorized that WM is limited in terms of "chunks", or a set of basic units that have been grouped together and vary based on an individual's prior categories and schemas for processing information (Miller, 1956). There are many benefits to chunking as it is an effective strategy for optimizing the limited capacity of WM. Moreover, chunking leverages meaningful schema in LTM by activating memories in semantic networks while minimizing resource demand (Collins & Loftus, 1975; Piaget, 1976).

Regardless of the model, WM is characterized as a limited capacity system. John Sweller's Cognitive Load Theory (CLT) describes how the limited resources of WM are used (Sweller & Chandler, 1991). There are three types of cognitive load: intrinsic, germane, and extraneous (Sweller, 2010). Intrinsic load describes the innate minimum load based on the nature and complexity of task (Paas, Renkl, & Sweller, 2003). While Sweller argues this cannot be altered as it is inherent in nature, some would debate that updating and enhancing the design of the information display can change the baseline learning of the load. Germane load is associated with prior knowledge and relates to the construction and commitment of schemas in LTM (Debue & Van De Leemput, 2014). This load can be influenced by instructional design methods and information display. Extraneous load describes the irrelevant information that becomes "noise" surrounding the task a user is focused on and does not appeal to schematic learning. Because of this limited capacity to handle load, split attention or "multitasking" results in competing tasks drawing on the same resource with both suffering as a result (Madore et al., 2020). The fundamental implication of CLT is performance will be raised when the limitations of WM are considered in instructional design and information display.

While it is important to consider the load imposed on the user and their WM capacity, performance also hinges on an individual's willingness, or motivation, to give effort. This resonates with Tversky and Kahneman's heuristics model of decision making as he proposed users will employ mental shortcuts when the load exceeds capacity and willingness to give effort (Tversky & Kahneman, 1974). Motivation is considered the great multiplier as predicted performance is higher with motivation (N. H. Anderson & Butzin, 1974). Whereas motivation is positively correlated with high performance, anxiety can affect performance in a negative way. A small portion of anxiety is good as it allows users to focus their limited attentional resources more fully, but there is also a threshold where that levels off and results in diminishing returns (Darke, 1988). Eysenck and Calvo's Processing Efficiency Theory describes the "performance deficits due to generalized anxiety" that are prominent in the specific tasks that draw on the limited capacity of WM (Eysenck & Calvo, 1992). Furthermore, because anxiety is considered a source of extraneous cognitive load, this leads to a detrimental allocation of some mental resources to emotional processing that otherwise would be devoted towards other cognitive processes such as assimilation and accommodation (Plass & Kalyuga, 2019).

Time Constrained

WM is also characterized by time constraints as new information in WM is temporary. The information is temporarily held before it becomes encoded in LTM, gets replaced, or decays. The predominant decay theory is the "time-based resource-sharing model" which proposes that representations in WM will decay unless that information is actively refreshed or rehearsed (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009). Estimates vary, but the duration of WM is on the order of seconds, with one estimate being around 10-15 seconds (Goldstein, 2014). The "time-based resource-sharing model" assumes that attention in WM is rapidly switched from processing a complex task to refreshing decaying memory traces before they are lost (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009). Certain factors can accelerate the rate of decay, such as visual or verbal competition in the same space, attention or level of engagement, and signal detection and discrimination of stimuli exhibiting just noticeable differences (Stanislaw & Todorov, 1999). The significance of this memory decay theory is its power in predicting the degree of "forgetting" relative to a task's temporal density, or cognitive load (Barrouillet & Camos, 2021).

Highly Volatile

Lastly, WM is highly volatile for various reasons. First, any chaos in the environment disrupts our rehearsal of data and these interruptions cause us to forget that information (Shrager, Levy, Hopkins, & Squire, 2008). Interruptions are detrimental to individuals who have entered "flow", the state in which one is intrinsically motivated to completely immerses themselves in whatever it is that they are doing (Nakamura & Csikszentmihalyi, 2014). When flow is interrupted, the person ceases to be in that state of effortless and enjoyable thinking. Studies suggest that people with autotelic personalities are more likely to experience flow state and that this personality is distinguished by high metacognitive skills because individuals who set and pursue goals central to one's purpose can theoretically attain a deep sense of meaning and fulfillment in their lives (Nakamura & Csikszentmihalyi, 2009). Second, WM errors are more likely to occur in a high load situation, and over time transposition errors occur first (Byrne & Bovair, 1997). When this error occurs, the right steps are accurately recalled, but the sequence of steps is out of order because the script was corrupted (Abelson, 1981). Later in time, intrusion errors might present according to the human memory Interference Theory, which describes how old and new memories compete and conflict with one another between LTM and WM (M. C. Anderson, 2003).

Case Review

Context

Ultrasound (US) examinations are difficult medical exams in which a technician ("ultrasonographer") must attempt to gain adequate views of internal organs using a probe that emits high-frequency sound. The US is performed in "real time" by the technician who must actively be interpreting the images and scans on the screen below at the bedside with the patient (**Figure 1)**.

Figure 1: Phillips Ultrasound Machine

When the exam begins, the ultrasonographer places the probe on the patient's body to start looking for the optimal position for the item of interest (e.g., fetus in a pregnancy ultrasound). In turn, they must manipulate the probe so that it eventually picks up the right areas of the body for examination. To acquire diagnostic quality images, the ultrasonographer is constantly adjusting the probe back and forth over the patient's body using subtle but expert hand motions that are guided by the images of the body being flashed on the screen before them. They must constantly be holding what they "just" saw in their WM as these images can be used to guide the next placement of the probe to a more ideal position over top of the patient's body. The visual information being stored in the ultrasonographer's WM must also be integrated with their LTM of how the exam is done, how the anatomy looks, etc. This knowledge is formed during arduous expert training by highly motivated students in medical or nursing school.

Analysis

The ultrasonographer is constantly processing visuospatial information as it appears on the US screen. For example, during the exam they must interpret the grayscale forms appearing frame-by-frame, correlate those to the most likely anatomic structure being imaged, and then integrate the current and previous frames with radiological medical knowledge to plan their next movements with the probe (**Figure 2**).

Figure 2: GE Ultrasound Probe

Coordinating this procedure imposes a very high, demanding cognitive load on the medical practitioner. Moreover, the central executive is firing off as the ultrasonographer must be careful about where to direct attention. These are images contain a high degree of "noise" due to complex layering of errant muscles, organs, blood vessels, bone, etc., which reflects Sweller's description of extraneous load. As a result, attention must be focused only on the most salient components of the screen that are pertinent to the exam while ignoring the noise, consistent with selective omission. Reflective of the time-based resource sharing model, the working memory of visual information in the US requires the operator to consistently refresh the decaying memories of previous frames or "chunks" of medical data by constantly using the previous images and metacognition to update their actions that will lead them to ultimately fulfill the goal of the exam. Moreover, there are many external conditions in this hospital setting such as other patients yelling in pain, nurses coming into get blood or change IVs, etc. that are very anxiety-provoking for the provider. This will negatively interfere with their performance as any interruption will cause the ultrasonographer to lose their train of thought, consistent with the highly volatile nature of WM.

Recommendations

Because of the demanding cognitive nature of performing an ultrasound, I would recommend always having at least two providers in the room for a medical examination so they can increase the shared working memory performance between them and better direct the probe during the exam. Secondly, US manufacturers, such as Phillips and Sony, should update the probe so that it can capture a screen image with the click of a button. Currently, the ultrasonographer must hold the probe in one hand and save or annotate the image with the other hand, which poses a high cognitive load on the provider. Lastly, I would suggest adhering to Norman's principle of "putting knowledge in the world" by standardizing on-screen buttons/modals that help the provider automate calculations and attach meaning to the image of the scan. For example, the measurement in the ultrasound below indicates the gestational age of the baby (**Figure 3**).

Figure 3: Fetal Ultrasound

Conclusion

WM is a limited capacity system that is time constrained and highly volatile. Baddeley's multicomponent model consisting of the phonological loop, VSS, central executive, and episode buffer is the predominant study in the field of WM. Sweller's CLT provides insight into how the resources of WM are allocated according to intrinsic, germane, or extraneous load. WM is distinguished from LTM by its demonstration of temporal decay according to the time-based resource-sharing model and Miller's "chunk" capacity limits. Emotions, such as anxiety and motivation, must be considered when designing interfaces as they influence WM ability. Furthermore, interruptions negatively impact WM as they terminate the rehearsal loop of information and cause us to lose hold of that data. Ultimately, WM is paramount to facilitating the critical cognitive functions supporting our well-being such as planning, reasoning, communication, and comprehension.

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