Research Note 2021-01

Visible Thinking: A Distributed Cognitive Process to Self-Manage Cognitive Load

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March 2021

United States Army Research Institute for the Behavioral and Social Sciences

U.S. Army Research Institute
for the Behavioral and Social Sciences

Department of the Army
Deputy Chief of Staff, G1

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REPORT DOCUMENTATION PAGE			Form Approved *OMB No. 0704-0188*
1. REPORT DATE *(DD-MM-YYYY)* March 2021	**2. REPORT TYPE** Final		**3. DATES COVERED** *(From - To)* September 2018 – April 2020
4. TITLE AND SUBTITLE Visible Thinking: A Distributed Cognitive Process to Self-Manage Cognitive Load			**5a. CONTRACT NUMBER** W5J9CQ-12-C-0004 **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 622785
6. AUTHOR(S) Peterson, Jared, J.			**5d. PROJECT NUMBER** A790 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER** 425
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Consortium Research Fellows Program, Consortium of Universities of the Washington 4214 King Street, First Floor Alexandria, Virginia 22301-1555			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Institute for the Behavioral & Social Sciences 6000 6TH Street (Bldg. 1464 / Mail Stop 5610) Fort Belvoir, VA 22060-5610			**10. SPONSOR/MONITOR'S ACRONYM(S)** ARI **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** Research Note 2021-01

12. DISTRIBUTION/AVAILABILITY STATEMENT:
Approved for public release, distribution unlimited.

13. SUPPLEMENTARY NOTES
ARI Research POC: Dr. KC Ejiogu Kingsley, Fort Leavenworth Research Unit

14. ABSTRACT

To make informed decisions, U.S. Army leaders must process large amounts of information, filtering it for relevance, and then synthesizing it to understand the operational environment. Identifying relevant information and processing the interdependences of that information can be cognitively challenging. This report summarizes recent literature related to reducing cognitive demand and increasing understanding of complicated information. The construct of visible thinking is introduced as a distributed cognitive process that reduces cognitive demand by externally representing thoughts in an observable manner to support further thought and communication. Visible thinking helps disperse information through underutilized processing channels to integrate information and develop new insights. The goal of engaging in visible thinking is to make more informed decisions by better understanding complicated information.

15. SUBJECT TERMS
Complex information processing, Self-management, Cognitive load, Cognition, Visualize

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Dr. Angela I. Karrasch
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	Unlimited Unclassified	33	**19b. TELEPHONE NUMBER** 913-702-5867

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VISIBLE THINKING: A DISTRIBUTED COGNITIVE PROCESS TO SELF-MANAGE COGNITIVE LOAD

EXECUTIVE SUMMARY

Research Requirement:

The U.S. Army faces increasingly complex operational environments, where Army leaders need to understand complex information to make informed decisions and shape future operational environments (Grome, Weyhrauch, Crandall, Polander, & Laufersweiler, 2020). Understanding complex operational environments is cognitively challenging when environmental factors and their interdependences need to be simultaneously processed to make sense of the environment (Paas, van Gog, & Sweller, 2010). The focus of the current effort was to review academic literature related to complex information processing, and methods for increasing the likelihood that an Army leader will understand interacting information and be able to make informed decisions.

Procedure:

A review of academic literature was conducted that included literature related to what makes complex information processing difficult, how the presentation of information influences processing, when to offload mental information into the environment to aid the processing of complex information, and how to self-generate or self-modify external representations (i.e., pictures and text) to help manage mental resources.

Findings:

The current literature has limited information on how an individual engages in self-managing their own mental resources using visible self-generated or self-modified external representations (i.e., images & text). Visible thinking is a distributed cognitive process in which an individual's thoughts are externally represented in an observable manner to support further thought and communication. For the purposes of this research note, the cognitive and behavioral aspects of visible thinking are the primary focus. Visible thinking can be reduced to a three-step process: 1) Developing internal thought; 2) Externally representing internal thought; 3) Coupling external representations with ongoing internal thoughts to support further internal thoughts. Visible thinking may include multiple iterative cycles between steps 2 and 3. Another way to think of the process of visible thinking is during conceptualization. If cognitive demand is high, that demand can lead to externalizing information for the purpose of cognitive offloading. The external representation can then either be stored for later use or immediately engaged with to support further thought. As thought advances with the use of the external representation, it may be necessary to modify the external representation, or create other external representations to continue supporting further thought.

Visible thinking is proposed to support understanding of complex information by dispersing information through underutilized processing channels, and by aiding in the integration of information and development of new insights. Army leaders who put greater priority on the performance goal of accuracy compared to the performance goal of speed are

likely to engage in the process of visible thinking more often. The expectation is that engaging in visible thinking will increase understanding and informed decision-making with complex information.

Utilization and Dissemination of Findings:

This literature review suggests that visible thinking is a cognitive process, which theory suggests can be managed or trained to amplify natural tendencies to understand our environment. If Army leaders were trained in visible thinking, it is possible that they would better self-manage their own cognitive load, and deeper understanding could be achieved and communicated. More research is needed to determine the conditions under which visible thinking is appropriate.

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The U.S. Army faces increasingly complex operational environments, where Army leaders need to understand complex information to make informed decisions and shape future operational environments (Grome, Weyhrauch, Crandall, Polander, & Laufersweiler, 2020). It is necessary to further develop Army leaders' cognitive abilities to assess the environment and anticipate changes. If Army leaders can anticipate changes in the threat environment, they have more time to create, plan, and resource options to address the coming threat (Sackett, Karrasch, Weyhrauch, & Goldman, 2016). However, understanding complex operational environments is cognitively demanding when environmental factors and their interdependences need to be simultaneously processed to make sense of the environment (Paas, van Gog, & Sweller, 2010). Having Army leaders that are better equipped to understand complicated and complex information more efficiently and/or effectively would be a combat multiplier. Training for visible thinking may be a solution to enabling this capability. Visible thinking is a distributed cognitive process that reduces cognitive demand by externalizing thought in a visible and stable manner to support further thought and communication. Visible thinking distributes information from a purely internal representation (mental concept) to the external environment as an external representation (i.e., image or text; Zhang & Norman, 1994) in an effort to reduce cognitive demand. An internal representation externalized to be an external representation can be engaged, and can reenter working memory by potentially tapping into underutilized processing channels, and aid in integrating information as well as developing new insights.

The purpose of this research note is to lay out the concept of visible thinking, and how Army leaders could use the concept to self-manage their own cognitive load to help them understand complicated and complex information more efficiently and effectively. Increased understanding, enabled by visible thinking, could lead to more informed decisions. The literature on information processing is discussed, along with related concepts that lead to the need for training for visible thinking.

Information Presentation Format Influences Understanding

One major problem with understanding information can be how the information is presented. For example, imagine receiving travel directions orally versus having a map that guides you to a location. If the directions simply require you to drive one mile straight and then take a left, then no map is required; the oral directions are sufficient. However, if the directions require you to make multiple turns at different distances, you might be more interested in having a map or, at the very least, start writing down the directions. Why? The brief answer is that directions with multiple turns present a lot of information to remember to successfully travel to your destination. A more elaborate, traditional answer is that working memory (WM) is limited in the duration and capacity of processing novel information (Baddeley & Hitch, 1974). The duration for novel information processed in WM is about 20-30 seconds from when it was stored in WM, unless the information is transferred to long term memory or rehearsed in WM (Peterson & Peterson, 1959). Cowan (2001) has argued that unaided working memory capacity (WMC) has a limit of 4±1 chunks of information, and that long-term memory capacity is virtually limitless. Cognitive load refers to the amount of working memory resources required by the learner (Sweller, van Merriënboer, & Paas, 2019). Cognitive overload can occur when the working memory resources are overtaxed (Sweller, 1988), which typically happens when a complex concept has a large number of elements that interact and require mental manipulation. Such element interactivity (Ayres, 2006) requires processing, storage, and rehearsal of the components of the complex concept. The cognitive overload can result in an increase in processing time for information, with possible errors, if the information is understood at all (Baddely & Hitch, 1974).

With such a constraint on WMC, what can be done to reduce the burden placed on WM? Cognitive offloading is a process by which internal information (i.e., mental thought) is externalized into the environment or the environment itself is manipulated in a manner to reduce cognitive demand (i.e., reduce internal information processing) (Risko & Gilbert, 2016). Essentially, generating an external representation involves taking a chunk of information that is being processed internally and transferring the information into the environment. Such information can be externalized on a piece of paper or a whiteboard making the external representation, which can either be actively engaged with as a new external resource or stored until relevant again. Think of the earlier example about travel directions. If someone gives you a complicated series of travel directions, you can offload the burden on WM by externalizing some of that information by writing down the directions on a piece of paper. Externalizing the travel directions can be an easier way to store the information and recall it when needed while driving to the location. Another option is to draw yourself a map, which also involves mentally offloading the travel directions, but in a pictorial form. Drawing yourself a map can make understanding the travel directions easier by incorporating spatial information that reduces searching through the information, and drawing yourself a map also makes it easier for the human perceptual system to group related information (Larkin & Simon, 1987).

Prior research from Dual-Coding Theory (Paivio, 1991) has shown that learning benefits can occur by processing verbal and nonverbal information in parallel (i.e., additive effect). Similarly, Baddeley's (1992) WM includes a central executive that coordinates parallel information process across two slave systems: the phonological-articulatory loop (i.e., auditory working memory), and the visuospatial sketchpad (i.e., visual working memory).

The dual-coding channels perspective has been accepted as a general assumption for the Cognitive Theory of Multimedia Learning (e.g., Mayer, 2001; 2009) and the Cognitive Load Theory (e.g., Sweller, Ayres, & Kalyuga, 2011). Both theories, Mayer's Cognitive Theory of Multimedia Learning (CTML) and Sweller et al.'s Cognitive Load Theory (CLT) have provided evidence for the benefit of dual-coding of verbal and visual information in parallel, also known as the modality effect (Ginns, 2005). However, Schnotz's (2014) Integrated Model of Text and Picture Comprehension (ITPC) highlights that while dual-coding can be beneficial to individuals with low prior knowledge of a given concept, dual-coding can also be redundant and detrimental to learning when an individual has high prior knowledge of a given concept. Therefore, while prior knowledge is generally an important factor, the utility of an external representation is going to be based on the complexity of the concept or process to be understood and how that external representation is designed.

Cognitive Offloading Increases with Problem Complexity

Prior literature on external representations (ERs) has focused on the interpretation and interaction of ERs that are presented to learners (Cox, 1999; Larkin & Simon, 1987; Zhang, 1997). However, ERs are not always present or optimally designed for an individual's understanding of a concept (Mayer, 2001; Sweller et al., 2011). An obvious solution to such problems is to self-generate an ER or manipulate/modify an existing ER that is poorly designed. Such actions can occur naturally when an individual believes it would be easier to construct or interact with an ER than to understand a concept through entirely internal cognitive processes (Kirsh, 2010).

When solving problems, students commonly use scratch paper or make notes next to questions on paper-based tests. However, the literature related to the use of scratch paper is limited. Prisacari and Danielson (2017) investigated the influence that different test modes (e.g., computer vs. paper) have on cognitive load. As an alternative measure of cognitive load, Prisacari and Danielson measured the use of scratch paper as well as the subjective cognitive load measures of perceived mental effort (Paas, 1992) and perceived difficulty (Bratfisch, Borg, & Dornic, 1972). Prisacari and Danielson (2017) also examined the objective measure of item difficulty with the item difficulty index (Ding & Beichnerk, 2009). Prisacari and Danielson found that college students used scratch paper mostly when solving algorithmic problems rather than conceptual or definition questions. Algorithmic problems require the use of memorized processes or procedures to be solved (Zoller, Lubezky, Nakhleh, Tessier, & Dori, 1995). As a process, solving an algorithmic problem often requires multiple steps, including intermediate steps (Smith, Nakhleh, & Bretz, 2010). For example, think of solving a calculus or organic chemistry problem by writing out a known formula on a piece of scratch paper and working out the solution with multiple steps (Marshall, 1997). A conceptual question "may be text-based or diagrammatic and require students to invoke underlying concepts of the basic theories of science in order to answer the question" (Zoller et al., 1995, p. 2). As defined, an interesting difference between algorithmic and conceptual questions is that conceptual questions are said to require a greater synthesis of underlying concepts to solve the problem than algorithmic problems; yet, algorithmic problems may require a greater number of bits of information to solve the problem. Therefore, there may be a difference between the conceptual size (amount of information) versus the number of items simultaneously required to solve the problem. WMC is much more restricted by the number of items that can be stored and manipulated than the amount of information contained within an item (Cowan, 2001; Miller, 1956).

Prisacari and Danielson (2017) hypothesized that conceptual problems were more likely to require more working memory resources than algorithmic problems. This hypothesis was based on Holme and Murphy's (2011) argument that algorithmic problems can be solved more often by applying heuristics whereas conceptual problems require more analytical thinking to be solved, resulting in a greater requirement of working memory resources. If the solution to a problem could be immediately solved by applying a heuristic, then perhaps Prisacari and Danielson (2017) would have found support for their hypothesis. However, Prisacari and Danielson suggested in their discussion that calculations were required for the algorithmic problems. If applying a heuristic is meant to mean applying a learned formula to solve an algorithmic problem, then following the calculation process of applying that formula to the problem may still require multiple steps to reach a solution (Smith, Nakhleh, & Bretz, 2010), which will require working memory resources to store and manipulate the values and operations needed.

Prisacari and Danielson (2017) found greater use of scratch paper for algorithmic questions than for conceptual questions. If the use of scratch paper is an indicator of cognitive load, then this suggests that algorithmic questions were more taxing to working memory resources than conceptual questions. CLT predicts this finding if element interactivity for solving the algorithmic problems is greater than the conceptual problems. An element is anything that needs to be "learned or processed, or has been learned or processed" (Sweller et al., 2011, p. 58). Ayres (2006) defines element interactivity as the number of elements that need to be simultaneously processed with working memory resources for the understanding of a concept, or in this case the solution of a problem (i.e., complexity; Sweller, 2010). While the conceptual problems may require the synthesis of large underlying concepts, if these concepts are learned concepts (i.e., schemas, Sweller et al., 2011), retrieved from long-term memory, then it may be no more difficult to store such a concept in WM than an initial, intermediate, or final value in a calculation (Cowan, 2001; Miller, 1956). CLT would predict that both the learned concept or schema and the initial value of a calculation are an element to be processed in WM. Element interactivity increases when the number of elements that need to be simultaneously processed increases (Sweller et al., 2011). In other words, there is greater element interactivity for simultaneously processing four pieces of information than sequentially processing four pieces of information. This last statement may initially sound like support for conceptual problems requiring greater working memory resources than the algorithmic problems. However, if solving the calculation for the algorithmic problem requires more elements be held in WM for a solution to be reached during multiple steps of the calculation, then there may be greater element interactivity for the algorithmic problem than the conceptual problem.

Epistemic behaviors (Kirsh & Maglio, 1994), such as writing or drawing on scratch paper, are an example of cognitive offloading where an individual is attempting to reduce the cognitive demand on working memory by placing some or all of the information into the environment (Risko & Gilbert, 2016). Making calculations visible on a piece of paper has long been considered as a "permanent working store," which is an "efficient substitute" of WMC (Hitch, 1978, p. 303). Hitch (1978) has previously shown with mental arithmetic that when the complexity of the problem increases, the calculation accuracy performance increases by having the problem presented in a stable visible format compared to an auditory presentation. These findings, interpreted through the lens of CLT, support the idea that cognitive offloading becomes more beneficial with increasing problem complexity. The next section discusses literature related to the benefits of self-creating or modifying external representations.

Self-Generating or Modifying External Representations

There is already a large body of literature on design principles for instructors preparing external representations for learners (Sweller et al., 2019), as well as on the interaction learners have with multimedia presentations (Mayers, 2009). However, premade learning materials are not always available or well-designed. The focus of this section is on the self-generation or modification of an external representation to aid understanding or later remembrance of concepts and processes, in relation to generating or modifying external representations: learner-generated drawings, the drawing effect, and self-managing effect.

Learner-Generated Drawing

Drawing has been investigated as a learning strategy (see Van Meter & Garner, 2005, for a review). A learner-generated drawing refers to a representational drawing that is created by the individual learning a given concept. Learner-generated drawings have been shown to be helpful in understanding to-be-learned content from expository textbooks (Alesandrini, 1981; Hall, Bailey, & Tillman, 1997; Leopold & Leutner, 2012; Schmidgall, Eitel, & Scheiter, 2019). The benefit of drawing is thought to derive from the dual-coding of verbal and image representations (Van Meter & Garner, 2005; Paivio, 1991).

Learner-generated drawings are composed of three factors: generation, externalization, and visualization (Schmidgall et al., 2019). Of the three factors, externalization and visualization are supported as being beneficial to the learner's comprehension of expository text. However, several studies have shown that the act of generating a drawing has a negative effect on the learner (Van Meter, Aleksic, Schwartz, & Garner, 2006; Leutner, Leopold, & Sumfleth, 2009; Schmidgall et al., 2019). Therefore, it may not be the act of developing the externalization that is beneficial, but the presence of having an externalization. (However, see later discussion about the motoric component in the Drawing Effect section.) Van Meter et al. (2006) has shown that drawing was only beneficial when accompanied with an illustration or an illustration with prompts. Learner-generated drawings are also perceived as more cognitively demanding than imagining content read from an expository text for the purpose of comprehension (Leutner, Leopold, & Sumfleth, 2009). Also, observing a drawing gradually exposed to the learner about content from an expository text has also been shown to be perceived as less cognitively demanding than learner-generated drawings and imagining (Schmidgall et al., 2019). The literature related to learner-generated drawings is full of examples of how having prepared materials are more beneficial than starting from scratch and creating representational drawings from text alone. However, and importantly, if you only have text, then making a representational drawing has been shown to increase understanding of expository text (Alesandrini, 1981; Hall, Bailey, & Tillman, 1997; Leopold & Leutner, 2012; Schmidgall et al., 2019).

Schmidgall et al. (2019) discussed the paradox of learner-generated drawings as being both an effortful process to produce the drawing, while also a process of cognitive offloading, which should reduce cognitive demand. Therefore, it is a tradeoff where the reduction to internal cognitive demand needs to outweigh the process of externalizing the given information. In other words, the use of a self-generated external representation must outweigh the cost of the externalization process (Zhang, 2000). The learner-generated drawing literature supports that when externalizing internal information into the environment, it is beneficial to produce a representational drawing of the concept or process that allows for a greater amount of parallel processing of information using both verbal and visual/spatial channels of processing. The drawing effect literature goes farther than just verbal or visual/spatial channels, but also has shown support that the motor component of generating a drawing can also aid in later recall (Wammes, Jonker, & Fernandes, 2019).

Drawing Effect

The drawing effect is a reliable finding that drawing a representational referent of a word results in better recall and recognition memory than repeatedly writing the word (Wammes, Meade, & Fernandes, 2016). The memorial benefit from drawing is said to be from its ‘seamless’ integration of three components: elaborative, motoric, and pictorial (Fernandes, Wammes, & Meade, 2018). The elaborative component is the generative process of bringing forth an internal representation for a word from its known semantic meaning and visual features. The motoric component is an active process where the actual behavior of translating one’s internal representation into an external representation is performed. The pictorial component is visually perceiving the referent produced during and resulting from the motoric component (Wammes et al., 2019). The benefit to recall and recognition memory from the drawing effect is said to be due to the multiple sources of information during encoding by producing a multimodal memory trace (Wammes et al., 2019). However, not all of the drawing components are necessary to see memorial benefits. For instance, Wammes, Roberts, and Fernandes (2018) have shown that just the preparation to draw a referent for a word, not actually drawing the referent (i.e., imagine condition), was enough to increase later memory for the to-be-remembered word compared to repeatedly writing the word. It should also be stated that actually drawing the referent for the word still out performed the preparation only condition. Drawing seems to provide a rich memory trace for specific items or words, but drawing has also been shown to hinder remembrance of the order that information was presented in (Jonker, Wammes, & MacLeod, 2019). Furthermore, Jonker et al. (2019) greatly attenuated the drawing effect by comparing drawing to silent reading by showing that drawing is beneficial to later recall when an individual is switching back and forth between drawing and silently reading words. However, when an individual is only drawing or only silently reading a short list of words, then there is a lack of a drawing effect or a reversal of the effect, such that reading silently resulted in greater recall of the to-be-remembered words from a short list than drawing.

Much of the drawing effect can be explained through the Cognitive Theory of Multimedia Learning – Multimedia principle that learning is better when both words and pictures are used than words alone (Mayer, 2009). Tasks that have shown evidence for the drawing effect typically start by showing the written word of the to-be-remembered item (e.g., “lion”), followed by a period of time where drawing, writing, imagining, etc., is taking place (Wammes et al., 2019). During the task, it is likely that the written word is being maintained in the phonological-articulatory loop in WM, while the visual representation is imagined, viewed, or created to be viewed in the visuospatial sketchpad in WM. Therefore, both the phonological-articulatory loop and visuospatial sketchpad are likely active and encoding both auditory and visual information resulting in dual-coding. Wammes and colleagues connect the drawing effect, like CTML and CLT Modality Effect, back to the Picture-Superiority effect and Dual-Coding Theory (Paivio, 1971). However, the drawing effect goes beyond just verbal and visual information and includes a motor aspect. The motoric component is said to enhance the memory trace of the to-be-remembered information by allowing another aspect to be encoded and integrated. However, the learner-generated drawing literature has found that the generation aspect of drawing is the most effortful process and the act of generating a drawing has a negative effect on the learner (Van Meter et al., 2006; Leutner, Leopold, & Sumfleth, 2009; Schmidgall et al., 2019). Perhaps, the difference is based on the tasks, the drawing effect literature has mostly had participants recall lists of words whereas the learner-generated drawing literature has mostly had participants read expository text books and draw out the concepts they are learning about. As discussed before, not all to-be-learned concepts require multiple chunks of information be simultaneously processed or held in WM warranting an externalization process, which if performed could result in an unnecessarily increased cognitive demand making it more difficult to understand the concept. However, with recalling lists of words, that is a complicated task with multiple words to be remembered. If the motor aspect from drawing the word results in the integration of encoded aspects of a given word resulting in a richer memory trace, then it stands to reason that the difference between these tasks is likely the reason that the two literatures differ on whether the generation/motoric component of an external representation is beneficial or not.

The learner-generated drawing and drawing effect literatures have shown support for self-generated drawings increasing comprehension and memory of to-be-learned or remembered items. However, the inclusion of a representational drawing is only one way of cognitively offloading internal information to one's environment to reduce cognitive load. The following section on the self-management effect discusses the effect and the importance of other external representations such as lines, arrows, and other relational symbols.

Cognitive Load Theory – Self-Management Effect

Cognitive Load Theory (CLT) has investigated and identified a number of design principles for instructors to implement in their instructional materials for their learners to more efficiently use their WM resources (Sweller et al., 2019). Cognitive load refers to the amount of working memory resources required by the learner, which are limited. CLT works within the human cognitive architecture, which has a framework where working memory has a limited capacity and long-term memory is unlimited (Sweller et al., 2019). The outcome from the research on CLT has been largely focused on what an instructor can do in designing materials such that their students are more likely to understand the instructor's materials. CLT has a long history of research providing evidence-based recommendations on how instructors should develop their materials to manage their students (learners) working memory resources to reduce cognitive load and result in increased understanding of the material (instructor-managed cognitive load) (Paas et al., 2010; Tindall-Ford, Agostinho, Bokosmaty, Paas, & Chandler, 2015). For example, a student may have a high cognitive load trying to understand an instructor's materials if there are a large number of elements interacting that need to be processed simultaneously in working memory to be understood. CLT's modality principle would suggest incorporating a diagram that visualizes the interactions of the elements, which should help reduce the cognitive load of the student and thereby increase the likelihood of the student understanding the to-be-learned concept (Marcus, Cooper, & Sweller, 1996).

The problem is that there is not always an instructor available to prepare a learner's materials based on CLT design principles. This same problem can be related to Army Soldiers who do not have a superior or subordinates that will spend the time to prepare information with an optimal design for their learning/understanding of the information. Thus, Army Soldiers who receives information presented to them in a poorly designed manner may be less likely to correctly understand the information presented. However, within the CLT literature, a recent and emerging area of research has focused on this very problem with student learners where, instead of the instructor preparing the instructional material through CLT design principles, the learner is taught CLT design principles and how to apply the principles to poorly designed materials. By having the learner modify and reorganize the materials with the learner's knowledge of CLT design principles, the learner is effectively self-managing his or her own cognitive load (self-managed cognitive load) to make it easier to learn the information (Agostinho, Tindall-Ford, & Roodenrys, 2013, Gordon, Tindall-Ford, Agostinho, & Paas, 2016; Roodenrys, Agostinho, Roodenrys, & Chandler, 2012; Sithole, Chandler, Abeysekera, & Paas, 2017; Tindall-Ford et al., 2015; for review see Mirza, Agostinho, Tindal-Ford, Paas, & Chandler, 2019).

The self-management effect is a fairly recent and under-investigated gateway into solving the *Missing Instructor Problem* as well as advancing the utility of CLT design principles. The self-management effect has primarily been investigated thus far with learning materials that lack spatially integrated text and pictorial information (Agostinho et al., 2013, Gordon et al., 2016; Roodenrys et al., 2012; Sithole et al., 2017; Tindall-Ford et al., 2015), which can produce the split-attention effect (Tarmizi & Sweller, 1988; Ginns, 2006). If fully understanding a concept requires the integration of both text and pictorial information, then spatially placing the text relevant to specific aspects of a picture reduces the required search and mental integration of the noncontiguous information (Chandler & Sweller, 1991; Chandler & Sweller, 1992). The split-attention effect is similar to the spatial and temporal contiguity effects in the Cognitive Theory of Multimedia Learning (Mayers, 2009).

Roodenrys et al. (2012) provided evidence that learners can be taught CLT design principles and apply the principles to poorly designed materials. Learners who self-managed their cognitive load by applying CLT design principles to materials that lacked integrated text and pictorial information (conventional problem presentation style) had better recall memory about the to-be-learned information and near transfer performance than the conventional and instructor-managed groups. The self-management group also had greater far transfer performance than the conventional group (Roodenrys et al., 2012). Much like the old *teach-a-man-to-fish* saying, the self-managed group was able to apply what they had learned to new problems that had the same instructional design problem (split-attention effect). The self-managed group also outperformed the instructor-managed group on the recall and near transfer problems. Sithole et al. (2017) also found that the self-managed group outperformed the conventional and instructor-managed groups based on recall and transfer problem performance. Also, the self-managed group reported lower subjective mental effort than the two other groups (Sithole et al., 2017).

The self-management effect literature is quite new and currently limited (Agostinho et al., 2013, Gordon et al., 2016; Roodenrys et al., 2012; Sithole et al., 2017; Tindall-Ford et al., 2015). The techniques for the self-management of cognitive load have thus far primarily been developed for poorly designed materials that cause a split-attention effect (i.e., separated text and pictures). The self-management techniques are drawing circles around related nearby information, drawing arrows or writing numbers to link related text and diagram information, and to highlight, underline, and circle key words (Roodenrys et al., 2012). These techniques reduce cognitive load by linking multiple sources of information into a "single, integrated source of information," which removes or reduces the need to visually search for detached information and integrate them while holding some of the information in working memory (Sithole et al., 2017, p. 220). Roodenrys et al. (2012) noted that further research would be required to investigate self-management of cognitive load techniques for other cognitive load effects. The current list of self-management techniques are all visual externalizations drawn or written to augment poorly designed materials. The primary reason provided for why these techniques reduce cognitive load is that the techniques aid in integrating multiple pieces of information and, in doing so, reduce search times where some information needs to be held in working memory while search for other necessary information is conducted by the learner to make sense of the information (Agostinho et al., 2013; Ayres & Sweller, 2005; Ginns, 2006; Roodenrys et al., 2012).

The self-management effect has provided evidence that learners can be taught CLT design principles and apply them on their own to help manage their own cognitive load with split-attention learning materials (Sweller et al., 2019). As discussed earlier, the techniques taught to manage one's cognitive load are visible externalization techniques to modify poorly designed learning materials (Roodenrys et al., 2012). However, what cognitive process does a learner engage in when applying the self-management of cognitive load techniques? In the next section, the concept of visible thinking is delineated.

Visible Thinking

Visible thinking is a distributed cognitive process in which an individual's thoughts are externally represented in an observable manner to support further thought and communication.[1] For the purposes of this research note, the cognitive and behavioral aspects of visible thinking are the primary focus. The process of visible thinking can be reduced to a three-step process: 1) Developing internal thought; 2) Externally representing internal thought; 3) Coupling external representations with ongoing internal thoughts to support further internal thoughts. Visible thinking may include multiple iterative cycles between steps 2 and 3.

Another way to think of the process of visible thinking is during conceptualization. If cognitive demand is high, that demand can lead to externalizing information for the purpose of cognitive offloading. The external representation can then either be storage for later use or immediately engaged with to support further thought. As thought advances with the use of the external representation, it may be necessary to modify the external representation or create other external representations to continue supporting further thought. Conceptualization is developing a mental thought (internal representation) about a situation/idea/relationship (i.e., mental model; Johnson-Laird, 1980; 1983). Externalization is the process of transferring a mental thought (internal representation) into the environment by creating an external representation of that thought (e.g., drawings, dots, lines, written notes, etc.; Kirsh, 2009b; Tversky, 2011b). Cognitive offloading is behaviorally externalizing internal information or manipulating the environment to reduce cognitive demand (Risko & Gilbert, 2016). External storage is offloaded internal

[1] Project Zero is a program based out of the Harvard Graduate School of Education, where a project called, "Visible Thinking" was developed (Project Zero, 2016). Harvard's usage of the word *visible* comes from the perspective of an outside observer. For example, someone who has entered a classroom and watches students actively completing Thinking Routine mini-strategies (Perkins, 2003; Ritchhart & Perkins, 2008), is able to observe the thinking of the students. In this report, *visible* is used in a different manner, meaning to make thought present and observable as an external representation such that one's own visual system can observe the externalized thought.

information that has been externalized in an effort to reduce cognitive load as it is information that is not currently relevant to internal processing, but is suspected to be important to future internal processing (Intons-Peterson & Fournier, 1986). Thus, external storage is a form of prospective memory (McDaniel & Einstein, 2000). However, externalizations (i.e., external representations) are more than just memory aids, they also "guide, constrain, and even determine the pattern of cognitive behavior and the way the mind functions" (Zhang, 2000, p. 4). Engagement is where externally supported information is coupled with ongoing internal operations through distributed processing (Cary & Carlson, 2001; Zhang & Norman, 1994). Successful use of visible thinking occurs when engagement results in furthering an individual's understanding of a concept, which would have been very cognitively demanding or potentially impossible if completed by internal processes alone.

Engagement

Engagement is the interaction between internal and external cognitive operations in an effort to resolve working memory capacity constraints to increase the likelihood of understanding a given concept or process.[2] The engagement process of visible thinking presumably results in task switching between internal and external processes as a dual-mode problem solver, which most importantly results in coupling internal and external information to advance thought (Bocanegra, Poletiek, Ftitache, & Clark, 2019). When processing complex information, the number of elements or pieces of information that need to be integrated or simultaneously processed in working memory can exceed the limitation of working memory capacity to gain a full understanding of the concept or process. In order to counteract working memory capacity constraints, the following two basic strategies can be used: process the information more efficiently or reduce the number of items being processed simultaneously. Engagement is primarily an effort to more efficiently process information by using external representations, along with ongoing internal representations to distribute cognitive operations to both internal and external workspaces (Zhang & Norman, 1994). However, engagement may also facilitate other cognitive operations such as chunking with the aid of distributed processing by using an external representation to offload partial bits or all of the information to be chunked. In addition to efficiency and potentially enhanced chunking capability, establishing an external representation allows for the use of projection (Kirsh, 2009b), and the potential to more easily generate additional insights (Chambers & Reisberg, 1985; Lewis, 1992; Suwa & Tversky, 2003; Suwa, Tversky, Gero, & Purcell, 2001). All the above techniques may result in enhancing the ability of a problem solver to understand the concept or process at hand and to increase the problem solver's likelihood of solving the problem correctly and potentially more quickly as well (given increasing complexity).

Efficiency and Accuracy

Internal mental representations cost attention and memory resources to both create and sustain those representations (Kosslyn, 1990). Zhang and Norman (1994) have provided evidence that incorporating external representations into problem solving reduces solution time,

[2] Casiti (2018) recently proposed Mode 3 (M3), which has great similarity to this reports' conceptualization of Engagement, though each developed independently of one another.

solution steps (efficiency), and the number of errors (effectiveness). Zhang and Norman concluded that external representations, compared to the use of only internal processes, may make problem solving easier by reducing the load on working memory through the perceptual availability of external representations (stability). Cary and Carlson (2001) found that external representations increased the efficiency of problem solving with novel tasks, which Cary and Carlson concluded was from distributing the "burden on working memory" (cognitive load) across both internal and external workspaces (p. 841).

Cognitive load can also be reduced by behaviorally altering the environment to make cognitive processes easier. Epistemic actions are physical behaviors performed that alter an agent's own internal computational state (Kirsh & Maglio, 1994; also see *Spractions,* Tversky, 2011a; 2011b). Epistemic actions will either reduce, make more efficient, or more reliable internal computational processes, thus, performing epistemic actions should be a "cost-effective allocation of the agent's time and effort" (Kirsh & Maglio, 1994, p. 514). Kirsh and Maglio have provided evidence that epistemic actions such as physically rotating an object compared to mentally rotating the object can result in gaining the same knowledge more efficiently and with less effort. Maglio, Matlock, Raphaely, Chernicky, and Kirsh (1999) have shown that physically rearranging Scrabble pieces increased word generation more than only being allowed to mentally rearrange the pieces. However, the results were a bit more complicated than that as the word generation increase was found only with the set of letters that was identified as the more difficult word generation set of letters (also see Fleming & Maglio, 2015). These findings suggest that the benefit from performing an epistemic action increases with increasing task complexity.

Influence of Performance Goals and Beliefs on Usage of External Resources

Weis and Wiese (2019a) had participants complete an Extended Rotation Task to determine if two objects, which were at varying angles of rotation, were the same or different. To make a decision, participants needed to either mentally rotate one object to see if it matched the other object or use an external resource (i.e., rotation knob) that rotated the object for them. Weis and Wiese manipulated participants' performance goals to favor speed or accuracy when determining whether the objects were the same or different, and they measured the usage of the external resource, reaction time, and response accuracy on task trials. Weis and Wiese showed that problem solvers engaged more with external rotation to solve the task when accuracy was more important than speed. Also, when the problem solver's performance goal was speed over accuracy, there was an increased usage of mental rotation only. However, both the speed and accuracy performance goals during the Extended Rotation Task resulted in a large amount of offloading (i.e., using the rotation knob). The reliance on offloading mental rotation to the external resource may be to reduce mental effort (Ballard, Hayhoe, Pook, & Rao, 1997; Weis & Wiese, 2019a). When problem solvers were forced to complete the rotation task with only internal or external strategies, internal strategies (i.e., mental rotation) was faster, but less accurate; whereas the external strategy (i.e., object in the environment rotates by using a knob) was slower, but more accurate. Thus, there is an internal versus external strategy tradeoff between speed and accuracy, and strategy selection appears to be influenced by an individual's goals.

In addition to Weis and Wiese's (2019a) main finding of strategy tradeoffs based on goals, they also found evidence that external strategies were favored when individuals were free to choose between external and internal strategies, possibly to increase accuracy while reducing mental effort at the cost of decreased speed. Risko and Dunn (2015) showed an overreliance on offloading when participants were instructed to remember two to ten letters. Participants were given the choice whether or not to write down letters presented to them on a piece of paper. The participants chose to write down the letters more than 40% of the time when only two letters were presented. Participants who were not able to write down the two letters recalled them correctly greater than 97% of the time. This finding clearly indicates that the participants did not need to offload the two letters, but still did so. Risko and Dunn provided evidence that participants cited "maximizing accuracy" (p. 71) as their primary reason for offloading, which is in line with Weis and Wiese's (2019a) findings that accuracy as a performance goal leads to more offloading behavior. The speed-accuracy tradeoff is also apparent from Maglio et al. (1999) who found that participants that did very little or no physical rearranging of the Scrabble pieces when they were allowed to do so consistently stated that "they thought they could move the letters faster in their heads than could on the table" (p. 5). This result further supports the idea that when speed is prioritized, offloading/epistemic actions occur less often and internal strategies are more heavily relied upon. Interestingly, Weis and Wiese (2019b) have also shown that an individual's beliefs about the reliability of an external resource for offloading influences the amount of offloading behavior. They found that participants offloaded less when external resources had low reliability compared to high reliability. Weis and Wiese also found that the belief that an external resource has a low reliability, when in fact it may have a higher reliably than believed, still resulted in less offloading behavior. Therefore, belief and performance goals appear to influence the usage of external resources.

Reducing or Integrating Items in Working Memory

An alternative solution to the working memory limited-capacity problem is to reduce the number of items that need to be simultaneously held in working memory for the concept to be understood. This action may require schema acquisition or chunking (Sweller et al., 2011). How much information can be held in working memory can be increased through chunking (Miller, 1956; Cowan, 2010). Chunking occurs when multiple elements are integrated into a singular chunk of information (Cowan, 2010). Cowan (2001) provides a simple example of chunking, inspired by Miller (1956), which is to recall the letters "fbicbsibmirs" (p. 90). Chunking the letters into known acronyms with the help of long term memory of FBI CBS IBM IRS, effectively reduces the number of items from 12 to 4, which is now within the capacity limit of working memory (Cowan, 2001). Visual short term memory can hold approximately four (±1) chunks of information, and each chunk can contain about four elements of information, making for about 16 elements that can be held onto (Luck & Vogel, 1997). The problem is that to understand a complex concept or process, it may require not only holding onto a number of chunks of information, but also the interdependences between those chunks, which may exceed WMC (Halford, Cowan, & Andrews, 2007). Therefore, with complex concepts and processes, there is a great amount of element interactivity, which is defined by Ayres (2006) as the number of elements (chunks) that need to be simultaneously processed with working memory resources for the understanding of a concept. But, chunked information temporarily removes access to the relations of the elements within the chunk (Halford, Baker, McCredden, & Bain, 2005).

Therefore, chunking is not necessarily a suitable information processing strategy when the number of elements (chunks) that need to be processed simultaneously exceeds working memory capacity limits. Halford et al. (2005) have shown that problem solving performance decreases and processing load difficulty increases as complexity increases (i.e., increasing element interactivity). Therefore, chunking is only a suitable information processing strategy if the underlying element interactivity is approximately four items of information or less (Halford et al., 2005). However, when such a dilemma is met, a possible solution is to offload some of the information into the environment to be processed by the perceptual-motor system (Wilson, 2002). Such approaches have been discussed in cognitive science as distributed cognition (Hollan, Hutchins, & Kirsh, 2000; Zhang & Norman, 1994), extended cognition (Clark & Chalmers, 1998), embodied cognition (Wilson, 2002), situated cognition (Kirsh, 2009a), grounded cognition (Barsalou, 2008).

Distributed Multi-Channel Information Processing

Externalizing internal information (i.e., mental thought) into the environment allows the perceptual system to process the offloaded external representation by utilizing perceptual grouping (Wagemans et al., 2012; Wertheimer, 1923/1938) untapped WMC subsystems (i.e., spatial vs. object subsystems; Woodman, Vogel, & Luck, 2001; Woodman & Luck, 2004), and alternately facilitate visual objects in the focus of attention while suppressing other objects held in WM (Thigpen, Petro, Oschwald, Oberauer, & Keil, 2019). Externalizing internal information allows the external representation to reenter WM through different processing channels is an extension of CTML and CLT modality principle using the multi-channel models of working memory (Baddeley, 1992) and dual-coding theory (Paivio, 1991) (also see multiple resource theory, Wickens, 2002). The reentry process extends the multi-channel process concept to also include the distributed cognitive workspace along with the sensory, perceptual, and working memory subsystem processes that can be used to intake external representations (Zhang, 1997; Zhang & Norman, 1994; Zhang & Patel, 2006), and aid the processing of complex information (Zhang, 2000). Furthermore, somatosensory and motor processing resources may be tapped into through behavioral interactions with the environment, such as by generating or modifying external representation (e.g., motoric component of drawing; Wammes et al., 2019), which may enrich the encoded information for better recall.

Visual processing subsystems within working memory have previously been researched (Woodman et al., 2001; Woodman & Luck, 2004). Woodman et al. (2001) showed that increasing the number of objects held in visual working memory (e.g., 0, 2, & 4 objects) while also completing a visual search task did not impair visual search. However, there was potentially an impedance to the onset of the search or the response. This finding was initially interpreted as suggesting that information processed during visual search may be completed at a perceptual level of processing and not initially require visual working memory processes (Woodman et al., 2001). However, Woodman and Luck (2004) further investigated this finding and showed that visual search was impaired by a concurrent spatial task. Together, Woodman et al. and Woodman and Luck provided evidence that within visual working memory there may be separate subsystems such that visual search shares resources with the spatial location of an object, but perhaps not with a separate subsystem that processes the color and form of an object. Therefore, externalizing certain types of information such as color and form of an object may have a different effect than offloading spatial information by changing the spatial arrangement of objects in the environment or just by making spatial information visibly present. This also connects back to the learner-generated drawings and the drawing effect literature because representational drawings provide not only form and possibly the color of an object, but will also provide inherent spatial information.

There are also examples more specific to spatial offloading. Fleming and Maglio (2015) have observed participants performing epistemic actions while interacting with letter pieces of the game Scrabble to generate words by using multi-level grouping and pooling strategies. Multi-level grouping occurs by spatially arranging the letter pieces in two or more groups (i.e., Group 1 = ER & Group 2 = ING). Pooling occurs when two or more letters are grouped spatially together and other letters are distributed around the grouped letters (e.g., Pooled Group = ING, other letters randomly located = R, E, A, & K). These epistemic actions may reduce the burden on the spatial visual working memory channel by offloading these letter groupings into the environment by rearranging the letters to match the internal groupings, which theoretically frees up some working memory resources to more easily search for words that can be generated with the remain letters and the grouped letters (Fleming & Maglio, 2015). Woodman and Luck (2004) showed that working memory resources were shared between visual search and the spatial location of an object. Therefore, by externally grouping the letters, the internal processes no longer need to maintain that internal grouping arrangement, but to simply perceive the externally grouped letters.

There may be additional benefits to externalizing internal groups of information beyond just spatial working memory resources. In effect, pooling and multi-level grouping are both strategies to reduce element interactivity by chunking information externally (e.g., "I" "N" "G" to "ING,"), which reduces the number of items to compare when searching for words internally (e.g., "INRG" vs. "R" + "ING" = "RING"). Furthermore, a possible explanation for the pooling and multi-level grouping strategies is to utilizing both facilitation and suppression selective attention mechanisms. Information facilitated in WM must be in the focus of attention, which may be limited to a single item such that if two items are simultaneously relevant, the items must alternate their presence in the focus of attention (Thigpen et al., 2019). However, the suppression of visual information may not require much or any visual (object) or spatial working memory to implicitly learned locations (Gao & Theeuwes, 2019). Physically grouping letter pieces in Scrabble may also be another way to offload some of the work for visual search by placing some tiles in more-likely-to-be-suppressed locations, to facilitate visual search through letters that have a greater likelihood of creating a word. It is an epistemic behavior to physically alter the environment by moving the letter pieces around for the purpose of reducing the number of objects to-be-processed. The reduction in processing comes from putting letter pieces less likely to create a word in learned suppression locations to avoid searching those letters until necessary. For example, the letters "Q" and "Z" may be put off to the side (learned suppression location), while "ING", "R", "C", are spatially grouped closer together. Also, ING can be arranged closest and in the specific order to see "ING" spelled out. This would ease visual search by reducing the search set size from five chunks ("Q", "Z", "ING", "R", & "C") of information to three chunks ("ING", "R", & "C") to be searched and then manipulated in WM for a combination that makes a word (e.g., "RING").

Insights from External Representations

External representations have been shown to provide insights into knowledge and skills that are not available from internal representations alone (Chamber & Reisberg, 1985; Reisberg, 1987). Chambers and Reisberg (1985) showed that ambiguous mental images (e.g., duck/rabbit) can be held in memory, but additional insight into the alternative view of the representation was not possible until the image was externalized by drawing the image, at which point all participants were able to state the alternative option (i.e., duck or rabbit) for the ambiguous image. In other words, if a participant initially saw the duck, then that participant was unable to see the rabbit until they drew the picture of the picture they had in their head. Upon seeing their drawing, then they could also see the rabbit. An example of externalizations aiding in insights for problem solving comes from Stylianou (2002). Stylianou found that experienced mathematicians who solved problems that they did not know the solution to tended to draw diagrams to inspect and gain insights as to how to solve the problem.

Another way to gain insights from external representations is through projection. Kirsh (2009b) explains that perception, projection, and imagination are all on a continuum of stimulus dependence. Perception "strongly depends on the physical stimulus" (p. 2311). Projection requires that an external stimulus be present to anchor on to and then project something that is not present. Imagination is "a mental representation of a nonpresent object or event" (Solso, as cited in Kirsh, 2009b, p. 2312). Projection views what is present and then sees what is possible. Through a "project-create-project cycle," (Kirsh, 2009b, p. 2310), projection can advance thought by starting with an external stimulus, augment the stimulus in some way, then externalize the augmentation into the environment by aligning the augmented reality with physical reality, and then projecting a new augmented reality from the modified physical reality. Through an epistemic act of changing the physical stimulus to match the projected augmented external stimulus, the initial projection has been cognitively offloaded into the environment, freeing up processing resources to start a new projection. How far someone can project before needing to externalize the projection to free up cognitive resources will be different for each individual. Importantly, the initial act of projection that is anchored onto a physical stimulus already provides an almost limitless potential for gaining insights from external representations. Kirsh (2009b) provided evidence of the benefit of projection over pure imagination by having participants play tic tac toe and manipulated whether the participants had a blank piece of paper in front of them, only the tic tac toe board was present, or the tic tac toe board was present and an X and O were also present above the board. Kirsh also manipulated the complexity of the task by using 3 x 3 (less complex) and 4 x 4 (more complex) tic tac toe boards. Kirsh found that only with the 4 x 4 tic tac toe board was there a benefit to having the table present, and the facilitated performance was observed in the weaker visualizers. Kirsh did not have participants play on a 5 x 5 board. However, had Kirsh further increased the complexity of the game (e.g., 5 x 5 board) the same facilitation to performance may have also been seen with the strong visualizers. Overall, projection may become more useful as complexity increases. Surprisingly, in the 3 x 3 board condition, 50% of participants performed worse when the tic tac toe board was present in front of them compared to participants that only had a blank piece of paper in front of them and fully imagined the game. Kirsh suggested that this result is evidence that projection may have a cognitive cost, but the tradeoff becomes worth it as complexity increases. This finding is similar to Schmidgall et al.'s (2019) claim that use of learner-generated drawings must outweigh the initial cost of generating the drawing.

Interestingly, both weak and strong visualizers reported preferring the presence of the board, which was not necessary for the strong visualizer. It is likely that both weak and strong visualizers had a performance bias for accuracy over speed given that they could lose if they failed to remember the locations of the X's and O's. This may be further support that when task performance is biased toward accuracy rather than speed there is a desire to use external resources. Also, because the strong visualizer did not need the external resource (i.e., tic tac toe board) present, again, an over-reliance or in this case a desire to be overly reliant on external resources is observed possibly to reduce mental effort and increase accuracy (Ballard, Hayhoe, Pook, & Rao, 1997; Weis & Wiese, 2019a).

Inspecting external representations to gain insights has also been practiced in the Soft Systems Methodology by building and inspecting rich pictures (Checkland, 2000; Lewis, 1992). Soft Systems Methodology is a learning system which attempts to understand real-world problems and the people and their interactions that exist within the problem situation to develop actions to improve the problem situation (Checkland, 2000). To understand the problem situation, a rich picture can be developed to understand the complexity of the human interactions to view the problem situation in a holistic manner (Checkland, 2000). However, there has been confusion whether a rich picture refers to having an abstract understanding of the problem situation or an actual drawn-out picture that can be inspected and presented to others (Lewis, 1992). In relation to visible thinking, the rich picture that is a physical drawing is of most interest, and should aid in the abstract understanding of a problem situation. For example, Cristancho (2015) discussed the use of rich pictures to understand complex problems. Rich pictures can help reveal insights that may not have been expressed if only words were used. The creation of a rich picture allows for the re-examination of the complex information by the drawer and the researcher (or other observers) who can probe questions to attempt to reflect and dive deeper into the meaning within the drawing (Cristancho, 2015).

Similarities and Difference between Visible Thinking and Rich Picture Methodology

Visible thinking has many similarities with rich picture methodology in that by externalizing information, that external representation (rich picture) can be used to further internal thought. Therefore, the behaviors and products created may at times be similar and look like the same process. However, rich picture methodology has its roots in systems engineering (Checkland, 2000). The rich picture is viewed as a tool to help gain insight into complex real-world problems. Visible thinking is a distributed cognitive process that attempts to explain when and how to externalize internal information to aid in furthering thought. In other words, visible thinking explains through a cognitive science perspective what makes building and examining a rich picture potentially aid in greater understanding of complex interactions, and being able to more deeply search for meaning in pictures. It is by cognitively offloading the internal information as a rich picture, an individual can distribute the processing of that information to hopefully free up some cognitive resources. The act of freeing up some cognitive resources can enable the individual to capture new insights by making new connections, which may not be otherwise possible if the individual is trying to visualize the information internally with too much mental effort (Kosslyn, 1990).

Conclusion

The U.S. Army continues to face increasingly complex operational environments that Army leaders must understand to make the best decisions and shape the future operational environments. Army leaders are challenged with synthesizing a large number of environmental factors, along with the interdependences of such environmental factors, in order to make informed decisions. Visible thinking is a process that could amplify Army leaders' abilities to more efficiently and effectively understand complex information and enable productive discourse (Karrasch & Gunther, 2014) about complex ideas.

Visible thinking is a natural behavior for many people when they are trying to understand complex information. Army leaders can leverage this natural tendency by improving their situational assessment, recognizing complexity, knowing how to externalize information, and externalizing information as soon as it becomes beneficial. Cognitive Load Theory design principles provide the basis for training strategies that Army leaders need to self-manage their own cognitive load (Roodenrys, Agostinho, Roodenrys, & Chandler, 2012).

Further research is needed to experimentally demonstrate the "trainability' of visible thinking. For example, how much training is required before a leader is proficient at self-managing their own cognitive load? What is the best method for training visible thinking? Under what conditions is visible thinking most effective and what is the impact of visible thinking under the wrong conditions (i.e., speed vs. accuracy tradeoff)? Finally, if visible thinking is empirically shown to support the understanding of complex information, then further testing should be conducted to identify what increases the use of visible thinking in a complex operational environment as part of a team.

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