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The Role of Working Memory in Maintaining Situation Awareness

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Basic and applied research suggests that working memory (WM) supports situation awareness (SA) in dynamic environments. However, the relationship between WM and SA has not been well articulated. The present paper explores the potential role of WM in SA-based tasks by a) using a well-established WM model to conceptually link the two concepts and b) empirically testing this link. A dual-task paradigm was used where participants tracked an object against a moving background. Periodically, participants were required to either predict where the tracked object would be or to search for it. In addition to the tracking task participants concurrently performed one of four load tasks that separately taxed each of the four WM components (i.e. verbal, visual, spatial and central executive control). As predicted by the multi-component WM model (Baddeley, 1986; Logie, 1995) performing the SA tasks (prediction and search) relied on different WM subsystems. It is concluded that prediction involves the verbal subsystem whereas target search involves the spatial subsystem. The results support the role of WM in maintaining SA in a dynamic environment.

SA and WM

WM is the cognitive mechanism where information is integrated, manipulated and possibly recorded. Researchers have shown that the ability to activate and maintain sub-goals and intermediate solutions in WM is the key to success in many cognitive tasks. On this view, WM is believed to support the generation and maintenance of representations of complex task-environments. WM is what allows chess players to store sub–goals and to plan and anticipate future moves (Robbins et al., 1996). WM has also been shown to underlie the ability to solve problems (Carpenter, Just & Shell, 1990), and to engage in spatial reasoning (Shah & Miyake, 1996)

Given the role of WM in complex cognitive tasks, it seems likely that WM would be linked to SA. In accord with this view, based on fMRI measures, Perez et al. (2000) concluded that pilots' performance in a flight path maintenance task primarily involves cortical regions associated with WM. These cortical regions were more strongly differentiated for expert pilots compared to novice pilots. Perez et al. concluded that (a) WM supports pilots' comprehension of flight path information, including the anticipation of future actions and (b) the representation of information in WM becomes better defined with experience. Caretta, Perry, and Ree (1996) found that the ability to form and follow tactical plans and to communicate and interpret tactical information (e.g. threat prioritization) is related to spatial and verbal WM subsystems. Gugerty and Tirre (1995) found that maintaining awareness of location and avoiding hazards was highly correlated with WM measures.

In applied research, WM is frequently referred to as an important mechanism supporting SA (see Durso & Gronlund, 1999). However, the link between WM and SA has not been well articulated.

The goal of the present paper was to examine and strengthen the link between WM and SA. A multi-component model of WM (Baddley, 1986; Logie, 1995) was used as a theoretical framework.

The Multi-component Model of WM

The multi-component model of WM includes three subsystems for the maintenance of information, an episodic buffer for interaction with long-term memory (LTM) and an executive control system. Each subsystem uses different representational codes; visual, spatial, verbal. These subsystems are responsible for maintaining task-relevant information such as intermediate solutions and subgoals in order to carry out cognitive tasks. There may be other storage systems within WM for representing information in other modalities but the visual, spatial and the verbal systems are well established through research. Neuroimaging research, for example, has found support for distinct spatial and verbal WM systems (Smith, Jonides, & Koeppe, 1996).

The WM subsystems might play a critical role in maintaining SA in a dynamic task-environment. Research suggests that the verbal subsystem maintains cues (possibly linked to larger action plans in LTM) used to monitor and control action (Baddeley, Chincotta, & Adlam, 2001). The verbal subsystem might therefore be important for keeping track of and switching between multiple tasks. The verbal system has also been linked to the ability to make complex causal inferences during text comprehension (Shah & Miyake, 1996). The spatial subsystem is a movement-based system that involves planning and executing physical movements as well as representing the path between objects or target sequences (Quinn, 1991; Salway & Logie, 1995). The spatial subsystem is known to play an important role in tasks such as spatial reasoning (Shah & Miyake, 1996), chess playing (Robbins et al., 1996) and navigating (Garden, Cornoldi, & Logie, 2002). The visual subsystem has been less researched compared to the verbal and the spatial system. It refers to a temporary visual store for information such as shapes and colours.

The episodic buffer is a recent addition to the multi-component model and refers to a limited capacity buffer that represents coordinated information from the subsystems and from stored knowledge in LTM (Baddeley, 2000). The episodic buffer therefore is the connection between processing and representation in WM, and stored knowledge in LTM.

Finally, the central executive is a dedicated, possibly multi-dimensional, control system that is responsible for coordinating information from the various WM systems. The central executive also handles attention switching and controls both encoding and retrieval of information (Baddeley & Logie, 1999).

Overview of the Experiment

Based on the multiple-component model of WM, it was hypothesized that maintaining SA will differentially involve the WM subsystems depending on the specific SA demands. In particular, the verbal subsystem was assumed to support task switching and prediction based on prior knowledge about the task environment. The spatial subsystem was assumed to be important for representing spatial layout and executing movement. The central executive would be associated with coordinating tasks and selectively controlling attention.

A dual task paradigm was used in which a tracking task was combined with different WM load tasks. In the tracking task, participants tracked a target rectangle on a display by controlling a second rectangle with a mouse. Their task was to keep the controlled rectangle on top of the target rectangle. In addition to tracking, participants were also required to a) predict the future location of the tracked target and b) search for the tracked target. Periodically throughout the tracking task the tracked rectangle (pink) changed colour. A change to blue meant that the rectangle would disappear and then reappear in the lower right corner of the display. This is referred to as the prediction condition because the change from pink to blue was a consistent cue that would allow the participant to predict the future location of the tracked target. A change from pink to yellow meant that the tracked object would disappear and then reappear in one of the four corners of the display (randomly determined). This is referred to as the search condition because the change to yellow indicated that the target would appear in a corner: the participant was required to search the corners of the display to find the target.

The experiment therefore represented a task environment where fundamental aspects of SA were important. Specifically, participants were required to maintain a representation of task-relevant information in order to quickly activate predict or search activities. In addition, participants were required to use knowledge to predict the future location of the target and to coordinate the tracking task. The use of specific WM subsystems during tracking was assessed by introducing different WM load tasks that individually tapped into different subsystems of WM; verbal, visual, spatial and central executive.

Tracking was expected to depend primarily on the spatial WM subsystem. However, predicting and searching for the target object was assumed to rely on the verbal and the spatial system respectively. In order to predict or search for the tracked object, participants were required to maintain task-relevant information in WM (i.e., information regarding the colours and their meaning) that enables them to engage either a prediction or a search strategy. The spatial subsystem should play a strong role in the search condition because effective search requires a spatial representation of the display layout and an understanding of the relevant distances between the controlled rectangle and each corner of the display. This spatial representation would presumably enable the participant to quickly spot the target when it reappeared and importantly, to elicit the correct control input to quickly and accurately get to the display corner where the target appeared. Spatial layout and representation of movement have both been associated with the spatial subsystem (Quinn, 1991; Salway & Logie, 1995). It is expected, however, that predicting utilizes the verbal system. It is plausible to assume that the verbal system might be used for maintaining cues for activating relevant knowledge in LTM ("if blue go to the lower right corner").

In general, it was expected that responses to shifts in target location would be faster in the prediction than in the search condition. Undifferentiated response times between the prediction and search conditions would indicate that the participants were unable to use the predictive information and stored action plans. It was also expected that the introduction of the prediction and search conditions would involve the central executive system in addition to the subsystems. In order to coordinate task-related knowledge and switch from tracking to predicting or searching for the tracked object, the central executive must be involved.

Method

Participants

A total of 17 undergraduate students (10 females, 7 males) from Carleton University volunteered for this experiment. Participants received course credit for their participation.

Apparatus, Stimuli, Design, and Procedure

The experiment was controlled using E-prime software. The visual display was presented on a 17-inch SVGA colour monitor. To provide enhanced realism, a map of the greater-Ottawa area was presented as background on the display. This map was shown in grey colour/tones and moved vertically up the screen at a steady rate.

The tracking task included two stimuli: a pink target rectangle and a red controlled rectangle, 1cm x 2cm in size. These stimuli were superimposed over the moving map: the red and pink colours were easily distinguished from the background and from each other. The pink rectangle moved along both x-and y-axis according to a pre-defined loop which was independent of the background map movement. The red rectangle was controlled by the participant using a mouse: participants were instructed to use the mouse to keep the red rectangle on the top of the pink rectangle. Data for the X and Y position of the two rectangles was collected at 10 Hz.

Participants performed the primary tracking task combined with one of 4 load tasks: discrimination of shapes (visual), rhyming (verbal), tapping a defined pattern on a keypad (spatial) and tapping randomly on a keypad (central executive). The tracking and load tasks were performed alone (single-task) and together (dual-task conditions). Hence, there were nine conditions for the experiment. Each condition consisted of ten 30-second trials. The nine conditions were presented in a random order to each participant.

Approximately twice in each 30-second trial, the target rectangle changed colour. A change from pink to blue indicated that the rectangle would reappear in the lower right corner (prediction). A change from pink to yellow indicated that the rectangle would reappear in one of the four corners (search). Participants were instructed to move (as quickly as possible) the tracking (controlled) rectangle to the corner where the rectangle reappeared. They then followed the (blue or yellow) rectangle as it joined the defined tracking loop at which time the rectangle became pink again and the normal tracking task continued for the remainder of the trial or until next colour change occurred. The time it took participants to move the controlled rectangle to the corner of the display where the tracked rectangle reappeared was measured.

Results

An alpha level of .05 was adopted throughout this research. For comparisons between individual conditions, 95% confidence intervals were used (Loftus & Masson, 1994). Rather than recalculating the difference between conditions based on planned comparison, confidence intervals allow for a simple (visual) heuristics where a difference between two conditions is judged to be significant when the confidence intervals of two conditions overlap by ¼ or less of the total interval. A significant difference between two conditions is also referred to as a critical difference and can be calculated by multiplying the confidence interval by the square root of 2.

RMSE Tracking

RMSE tracking was analyzed in a one-way repeated-measures ANOVA of load task (baseline, verbal, visual, spatial and central executive). A significant effect of load task on tracking, $F(4, 64) = 14.917$, $MSE = 5.051$, indicated that tracking was generally worse in the dual-task conditions than in the single-task tracking condition. More importantly, the spatial task resulted in significantly larger tracking RMSE as compared to the single-task condition as well as the verbal and the visual conditions. This provides support for the notion that tracking involves the spatial, movement-based subsystem of WM. The central executive task (random tapping) resulted in similar decrements in tracking performance to those in the spatial task condition, suggesting that tracking did not involve additional central executive resources.

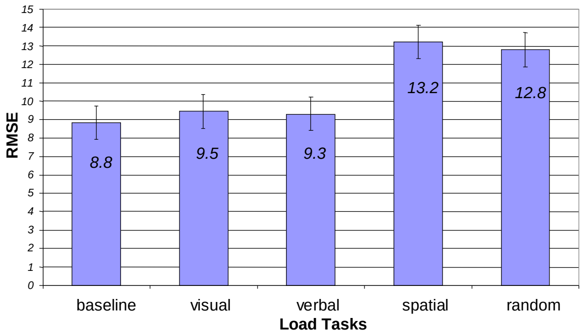

Figure 1. *RMSE for baseline (tracking only) and tracking with the different load tasks.*

Prediction and Search

The time it took participants to move the controlled rectangle to the correct corner where the tracked rectangle reappeared was analyzed in 2 (task: prediction vs. search) by 5 (condition: single-task, dual-task visual, verbal, spatial and random) repeated-measures ANOVA. As expected, there was a significant main effect of task, $F(1, 15) = 58.44$, $MSE = 39805.53$, and of condition, $F(4, 60) = 2.72$, $MSE = 10869.96$. The analysis also revealed a significant task by condition interaction $F(4, 60) = 7.24$, $MSE = 8511.12$.

The 95% confidence intervals (see Figure 2) show that participants were quicker to respond when they could predict the location of target rectangle as compared to when they had to search for the target. This shows that participants were able to use knowledge to predict target location.

Of primary interest was that the verbal task caused significantly more impairment in predicting the target location than the spatial task. This supports the hypothesis that predicting involves the verbal subsystem in WM.

For search, only the spatial task resulted in significant impairments relative to the single-task condition. This supports the hypothesis that searching for a target location depends on the spatial subsystem in WM.

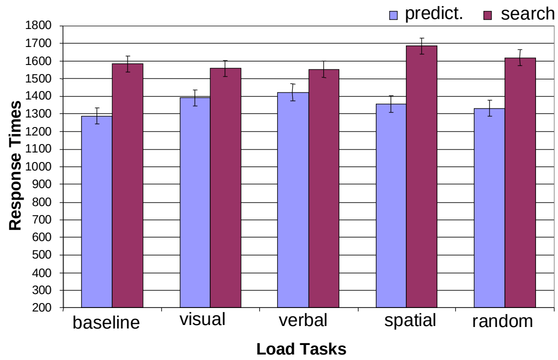

Figure 2. *RTs for moving the controlled rectangle to the corner where the tracked rectangle reappeared.*

In sum, the results show that prediction of a target location involves mainly the verbal WM subsystem whereas search for a target location primarily involves the spatial subsystem. The central executive control system did not play a particular role in the SA based tasks tested here. Analysis of the load tasks revealed increased error in random tapping (central executive task) while participants were engaged in search or prediction. The increased error might indicate that participants shed the central executive task in order to engage in search or prediction suggesting a role of the central executive system in coordinating the tasks and selectively controlling attention.

Conclusion

The present experiment supports the notion that WM subsystems differentially support SA in complex task environments. Specifically, it was shown that the verbal WM subsystem supports SA related to the prediction of target location, whereas the spatial subsystem supports SA related to target search.

Previous research has suggested a role for the spatial subsystem in maintaining navigational awareness (Arez, 1991; Gugerty, 1997). The unique contribution of the present experiment is in showing that the verbal subsystem also supports specific aspect of SA. By maintaining active cues in the verbal subsystem, participants could quickly retrieve the task-relevant knowledge (e.g., if blue move to the lower right corner) to predict target location.

The results provide support to the literature which has suggested a complex role of WM in supporting SA. For example, Caretta et al. (1996) found correlations between SA and spatial and verbal WM tasks as well as between SA and spatial reasoning tasks. Gugerty and Tirre (1995) reported correlations between SA for surrounding traffic in a driving simulation and various WM measures. Similarly, Aretz (1991) found that when pilots had to control a simulated aircraft and perform a difficult navigation task they switched from using spatial WM to using verbal WM. The present study extends those findings by showing that SA is supported by maintaining and updating information in both the verbal and the spatial subsystems. Further studies are needed to better understand the link between SA and the various WM systems, in particular the central executive control system and the episodic buffer.

Few attempts have been made to connect SA to underlying cognitive mechanisms. One reason for this is that SA is commonly viewed as a process or representation that an operator can consciously introspect upon (Endsley, 1995). Accordingly, researchers have often used conscious reports as a primary measure of SA and the cognitive mechanisms that are fundamental to generating and maintaining SA have been of little interest. The present research, however, suggests that SA can be conceptualized in terms of specific WM subsystems.

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