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Visual Search Versus Memory in a Paired Associate Task

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The Digit Symbol Substitution Test (DSST) has been used to study various effects, like aging and fatigue. Multiple cognitive and perceptual processes, like associative memory and visual search, are prominently utilized in the DSST. Understanding how these processes contribute to execution of tasks like the DSST is important to human factors research, as moderators like age and fatigue may differentially affect these processes. This study investigates performance on variants of the DSST that emphasize either visual search or associative memory with experimentation and computational cognitive modeling. While there are similarities in performance across task variants, the observed data suggests that, when visual search is possible, people appear to not utilize memory to the extent they would if relying on memory alone. The modeling suggests that behavior differences in the DSST variants results partly from procedural (i.e. strategic) choices and partly from the demands of the tasks.

INTRODUCTION

People utilize many cognitive, perceptual, and motor processes when accomplishing real-world tasks. In order to know how people perform these tasks, a better understanding of how different processes contribute differently to task performance is required. This, in turn, will allow a better prediction of how a diversity of circumstances will affect performance.

One task that utilizes visual search and associative memory, and has been used extensively to understand issues important to human factors research, is the Digit Symbol Substitution Test (DSST; Wechsler, 1997). The DSST was developed in the context of intelligence testing where it is used as a component of the WAIS-II. It has also been applied to understanding the effects of sleep restriction (e.g. Van Dongen, Maislin, Mullington, & Dinges, 2003) and the effects of aging (e.g. Joy, Kaplan, & Fein, 2004).

The DSST involves identifying what number is paired with a symbol. In the standard version, there are 9 symbols paired with the numbers 1-9. Participants are shown a symbol and respond with the corresponding number, completing as many trials as possible in a 3-minute time period. Because the symbol-number associations are displayed throughout the task (see Figure 1), common usage of the task is based on the premise that the task is driven primarily by visual search and perceptual motor mechanisms.

Even if DSST performance relies primarily on perceptual and motor mechanisms, there are ways that other cognitive capacities may influence behavior. For instance, because associations between symbols and numbers are consistent, associative memory could allow participants to retrieve the correct response, rather than look it up. In addition, the locations of symbol-digit pairs are consistent and ordered left-to-right in ascending order of the digit throughout the task, allowing spatial memory to be leveraged in performing the task. Thus, in contexts where the DSST has been used to understand the consequence of cognitive moderators like fatigue, it is difficult to isolate particular implications for specific components of cognitive processing.

To understand human performance on the DSST in more detail, Moore, Gunzelmann, and Gluck (2008) developed an ACT-R model that performed the task and captured the learning trends observed with extended experience with the task (i.e., 33 sessions lasting 3 minutes each, distributed over several days). This model makes important claims about how visual search and motor processes were affected by learning in the DSST. Unfortunately, the nature of the task made it difficult to validate the claims in that model, due to the interacting contributions of perceptual, cognitive, and motor processes to overall performance.

The aim of the research described in this paper is to better understand tradeoffs between complementary perceptual and cognitive functions utilized in a task, and how these tradeoffs may change with learning. Specifically, this research will study the DSST by utilizing novel variants of the task that effectively isolate visual search and associative memory, allowing for a detailed look at how these components of cognition contribute to overall performance.

EXPERIMENT

Participants

Eighteen people, 11 female and 7 male, ranging in age from 22 to 40 years of age (mean = 28.4) from the community around the Air Force Research Laboratory's Mesa Research Site in AZ participated in the experiment. Participants were screened as follows: 22 to 40 years of age; no known psychological, learning, or physical disorders or disabilities;

Figure 1. An example layout from a Moving-Pairs DSST variant trial. The target symbol is the forward slash at the bottom. The legend showing the digit-symbol associations is shown at the top.

normal or corrected to normal vision. Participants were paid $15 to participate in the 1 hr. study.

Tasks

The DSST variants used in this study are consistent with the DSST used in earlier studies (Van Dongen et al., 2003), with modifications to highlight different contributions to performance. Three variations of the DSST were:

Moving Pairs - This was similar to the standard DSST in that the symbol-number associations remain consistent, however the left-to-right ordering of the symbol-digit pairs changed on every trial. This variant was introduced to remove spatial memory from contributing to performance.

Changing Pairs - This was similar to the Moving Pairs variant, except that the symbol-digit associations changed on every trial as well. This variant was introduced to remove associative memory from contributing to performance.

Pair Memory - On each trial, at most one pair was shown in the legend. The symbol-digit pair containing the stimuli symbol was shown in the first trial in which that symbol was used. Otherwise the legend was not shown. This variant was introduced to remove visual search from contributing to performance.

In addition to these three variants of the DSST, the experiment included a fourth task, which we will refer to as "Digit Only." In this task, a single digit between 1 and 9 was displayed on the screen for each trial. The task simply required that the participants type that number using the number row on the top of the keyboard. This variant was introduced as a baseline condition to get an overall sense of typing speed, and also to assess whether there were any improvements associated with perceptual-motor aspects of performance. Participants completed two other tasks in the experiment, including the standard version of the DSST. Those tasks are beyond the scope of this paper, and are not considered in the analyses or discussion below.

Figure 1 shows a sample trial from the Moving Pairs variant. The legend, when it appeared, always appeared at the top of the screen. Digits were placed above the symbols. The maximum angle subtended by the symbols and digits was 1.2°. There was 1.1° vertical spacing between the digit and symbol in each pair, and 1.9° of horizontal spacing between each pair. The target symbol appeared 8.7° below the legend and was centered horizontally on the screen. The box surrounding the target symbol was 2.7° square.

Procedure

Participants performed all task variants in one session. Each task continued for six minutes, in contrast to the standard 3-minute duration of the DSST, to provide greater evidence regarding the learning trends. The participants completed as many trials as they could in that time. The task order was counterbalanced using a Latin Square.

Each trial proceeded as follows: All stimuli appeared. The participant responded. Feedback appeared for 1000 ms. The screen was blanked for 200 ms. The next trial started. The feedback showed the correct response above the target stimuli, and indicated whether the participant made an error (red "X") or not (blue "✓") beneath the target stimuli. An error was recorded if the participant did not respond after 10 seconds.

Before performing any of the tasks, participants received detailed, written instructions on how to perform each of them, with example screenshots from the task included to highlight the differences. The participants were presented with instructions for each specific variant again before performing that variant.

Results and Discussion

The analysis concentrated on the effects of the DSST variant (multi-level factor) and time on task (i.e. minutes conducting the task variant; continuous factor). Participant was used as a repeated-measure grouping factor. Linear mixed-effect models and post hoc comparisons were used for the analysis, using the R environment (Hothorn, Bretz, & Westfall, 2008; Pinheiro, Bates, DebRoy, Sarkar, & the R Development Core Team, 2010).

Figure 2 shows the mean reaction time of error free trials as a function of task and time on task. Response time was faster in some tasks than others, $F(3, 9751) = 2743$, $p < .001$. Response time also decreased with time on task, $F(1, 9751) = 364$, $p < .001$. Further, response time decreased more over time for some variants than for others, $F(3, 9751) = 80$, $p < .001$. As can be seen in Figure 2, the changing-pairs and digit-only conditions bracketed participants' response times. Very little learning occurred on either task within the six minutes. Post hoc comparisons using Tukey HSD test revealed that moving-pairs response time decreased faster over time than changing-pairs, and that pair-memory response time decreased even faster.

Figure 3 shows the proportion of error trials as a function of task and time on task. Task variant affected participant error rate, $F(3, 407) = 82$, $p < .001$, and error rates decreased with time on task, $F(1, 407) = 24$, $p < .001$. Error rates decreased more in the paired memory condition, as revealed by a significant interaction between variant and time on task, $F(3, 407) = 39$, $p < .001$.

In order to assess whether there were improvements associated with perceptual-motor aspects of performance in these tasks, a separate analysis was performed as a function of block order in the digit-only variant. Neither response time, $F(5, 12) = 1.28$, $p = .34$, nor error rate, $F(1, 16) = 3.97$, $p = .06$, improved throughout the experiment. Performance in the digit-only variant remains consistent throughout the experiment, suggesting that basic perceptual-motor processes were largely unaffected by experience in this task.

As the focus of this research is on the how visual search and memory are brought to bear on tasks as learning occurs, we consider the visual search only (i.e. changing-pairs variant) and associative memory-only condition (i.e. the pair-memory variant) separately before looking at performance on the moving-pairs variant in more depth.

Performance in the changing-pairs variant is consistent, suggesting that little learning in visual search processes occurs in six minutes. Further, early response times and error rates

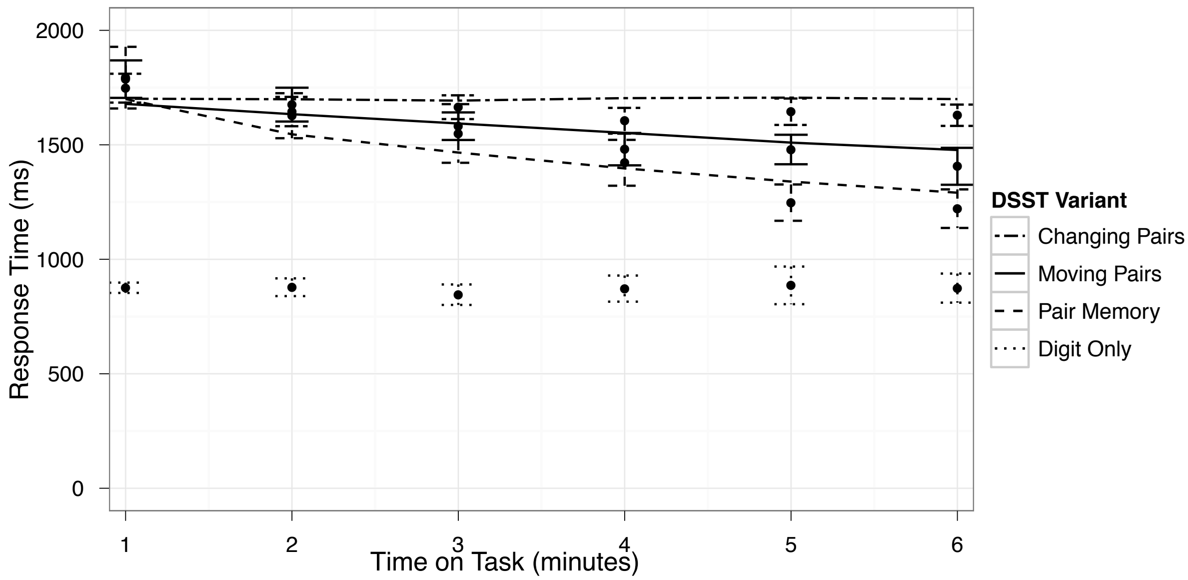

Figure 2. Observed response time (points & error bars) and predicted response time (lines) response time of error-free trials as a function of the DSST variant and time on task. Error bars show ±1 standard error of participant means.

are similar in the moving-pairs and changing-pairs conditions, illustrating the expectation that visual search initially dominated performance in the moving-pair condition.

The use of associative memory is evident in the task variants where it provides a potential benefit. Performance in the pair-memory variant follows the usual performance characteristics of paired-associate memory; response times and error rates are higher at the start when the associations are being acquired. In later trials, the participants respond faster and more accurately. Interestingly, by the sixth minute participants respond faster and with equivalent accuracy in the pair-memory condition as they do in the moving-pairs condition.

The moving-pairs condition is a bit more complex. In this task, the participants could use both visual search and associative memory. There is evidence that participants did use both, to varying degrees. Participants' response times in the moving-pairs variant are faster by minute six than when visual search alone is used, but slower than when memory alone is used. Still, participants' error rates in the moving-pairs variant remain equivalent to error rates observed when the participants used visual search alone. These two observations together suggest that the participants were speeding responses, when possible, by retrieving paired associations, but were maintaining accuracy by utilizing perceptual-motor processes (i.e. memory-in-the-world) when that requires less effort (Gray & Fu, 2004).

The results seem to indicate that any study utilizing the DSST must understand how both visual search and associative memory are involved in performance on the task. Visual search provides a baseline of response time and accuracy. And while associative memory allows people to improve their performance over time, people appear to not utilize memory to the extent they would if relying on memory alone. A

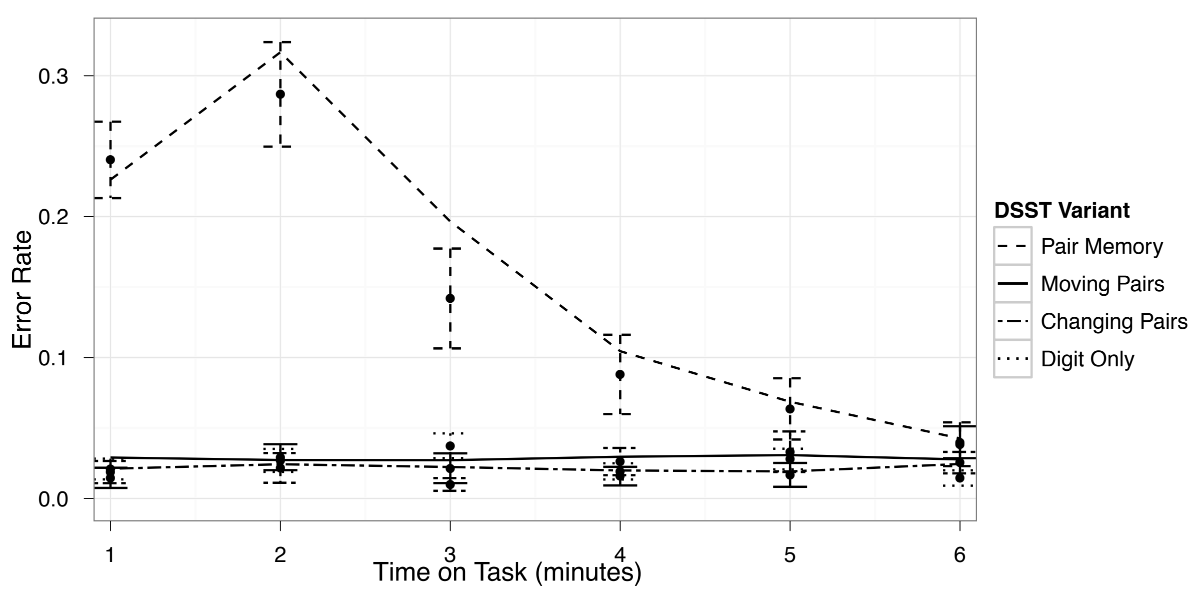

Figure 3. Observed error rate (points & error bars) and predicted error rate (lines) as a function of the DSST variant and time on task. Error bars show ±1 standard error of participant means.

computational model of the tasks was constructed to better understand the interactions between visual search and memory in the task variants, and to provide a testable account of that understanding.

MODEL

A computational model of the task variants was created in the ACT-R cognitive architecture (Anderson et al., 2004). ACT-R is a general theory of human cognition, including cognitive, perceptual and motor processes. The ACT-R cognitive architecture is a computational instantiation of that theory. For the current model, it is critical that ACT-R incorporates mechanisms for perceptual-motor action along with a well-validated theory of how the frequency and recency of use of declarative knowledge influences the availability of that knowledge.

The model allows us to explore how experience with the task impacts the interaction between perceptual-motor and associative memory processes. The performance of the model is shown in Figures 2 and 3, along with the human data. To obtain those fits, we varied parameters impacting the associative memory processes. The ACT-R parameters varied were: retrieval threshold (rt), which determines the minimum activation required to retrieve a memory; latency factor (lf), which in part determines the time required to retrieve a memory; and base-level learning (bll), which determines how quickly activation decays.

The foundation for the model is a visual search strategy for performing the task. The target symbol is attended and a visual feature of that object is selected at random. Attention is then repeatedly moved to the left-most object, which has not been attended and that shares the selected feature in common with the target. Visual search terminates when the target symbol is found in the legend, at which time attention is moved to the digit above that symbol. That digit is encoded and the model responds by pressing the corresponding key on the keyboard. The pre-defined features represent: (a) the orientation of lines in the symbol (horizontal, vertical, and diagonal), (b) whether the symbol is symmetric, (c) whether the symbol contains a filled shape, and (d) whether there is repetitive features in the symbol (e.g. double lines).

In addition to visual search, the model also has the capacity to retrieve the correct response from memory. Each time the target symbol and digit are attended, an imaginal representation of that information is created and placed in declarative memory. This knowledge is then available on future trials, potentially leading to a response without the need for visual search if the response is recalled before the target symbol is found visually. This retrieval process is conducted in parallel with visual search as the model performs the tasks.

The model explains the data in the changing-pairs variant very well (response time: rmsd = 64 ms; error rate: rmsd = 0.008). Since the observed data is quite flat, the r^2 of the predictions are not shown because they provide misleading information about the fit of the model to the human data. In the changing-pairs variant, since the associations between symbol and digit changed every trial, the model relies exclusively on visual search to determine the answer.

The model also accounts for the data in the pair-memory variant well (response time: rmsd = 78 ms and r^2 = 0.96; error rate: rmsd = 0.027 and r^2 = 0.95). The model rehearsed the associated pair prior to response (i.e. an additional iteration of attending and encoding of the correct symbol-digit, and a subsequent increase in activation of that information in declarative memory).

Interestingly, this strategy in the model accounts for the relatively long response times for participants on the first presentation of a symbol-number pair in this condition. Response times for these trials are relatively long, even though the correct response symbol-digit pair is shown alone in the legend. The best fitting model used declarative memory parameters of: retrieval threshold = 0.2, retrieval latency factor = 1.4, and base-level learning = 0.4.

The moving-pairs variant is the critical task in the experiment, since performance in this case can emerge from the interaction of visual search and associative memory processes. The data suggest that both processes are involved, and the model provides an account of how (response time: rmsd = 64 ms, r^2 = 0.96; error rate rmsd = 0.011). Whereas the model provides a relatively good account of performance, the best fits are obtained when the model does not rehearse the associated pair an additional time and when varying the declarative memory decay rate (i.e. base-level learning). Using the value of 0.4 from the pair-memory variant led the model to learn the associations too quickly, such that it was responding based almost entirely on memory by the end. Thus, the results shown in Figures 2 and 3 reflect a base-level learning (i.e. memory decay rate) value of 0.5, which is a standard value for this parameter.

DISCUSSION

This research reveals aspects of the complex interaction between visual search and memory in a paired associate task. This study was designed, in part, to tease apart the contributions of visual search and associative memory to task performance. The results provide support for conclusions regarding each of these functions.

The observed data and computational modeling of these task variants suggests that the observed behavior results from both procedural (i.e. strategic) choices and the demands of the task. People appear to purposefully rehearse the associated pairs in the pair-memory variant, leaving the memorization of associations to “implicit” processes in the moving-pairs variant. Further, the modeling requires parameter differences that potentially reflect participants’ “attentional” focus required by the task. Previous research has varied the same parameter to explain the effects of practice spacing (Jastrzembski & Gluck, 2009) and fatigue (Halverson, Gunzelmann, Moore, & Van Dongen, 2010). Additional research is required to identify the source of variation in the decay rate of declarative memories in the current task, and how that variation may relate to the spacing affect and fatigue.

One possible explanation is that greater "effort" to memorize the content corresponds to a slower decay rate. This would make sense in the pair memory condition, where associative memory was the only mechanism available for responding correctly, and this resulted in a slower decay of those memories. Further, it is possible that the difference in decay is a result of the type of learning used in the task, with the pair-memory variant eliciting "explicit" learning and the moving-pair variant eliciting "implicit" learning. Another possibility is that the participants exerted more effort by rehearsing some or all the associations in the "downtime" between trials. However, if this is the case, it is unclear why participants would do so in both the pair-memory and moving-pairs conditions. Additionally, when, how often, and which pairs are rehearsed is difficult to extract from the human data. The net effect of these strategies, however, is to increase the availability of the associations on later trials. In the current model, using a lower decay rate for that task variant produces this effect.

Previous research using the DSST found effects that may stem from memory issues but instead attribute these effects to other processes, arguably without a complete understanding of the tradeoffs between visual search and memory in the task. Much of the previous research (Joy et al., 2004; Stephens, 2006) has made the explicit assumption that fixations on the legend are evidence that participants are not responding based on retrieved memories. However, the computational modeling provided in this research shows that the data can be explained by visual search and memory retrievals for the response being performed in parallel. Therefore, if we are to understand how tasks that closely parallel the DSST are affected by cognitive moderators, like age (Mitzner, Touron, Rogers, & Hertzog, 2010), then we must have a better understanding of how the various cognitive and motor processes interact and contribute to observed performance. The current research moves us closer to understanding such interactions.

CONCLUSION

This research increases our understanding of the interplay between visual search and memory processes in a task that has been used previously to understand human intelligence (Wechsler, 1997), the effects of sleep (Van Dongen et al., 2003) and the effects of aging (Joy et al., 2004). The human data and computational cognitive modeling of the DSST variants reveal some aspects of how visual search and declarative memory processes interact to produce more complex behavior.

This research illustrates that studies should not assume that tasks like the DSST are clean measures of visual search or memory in isolation. However, the DSST and its variants presented in this research are useful for understanding differential effects on visual search and associative memory. The data and modeling suggest that any increase in the effort required to retrieve declarative knowledge (e.g. due to fatigue) will push the moving-pairs task execution towards visual search, thus potentially revealing a differential effect on visual search and declarative memory.

While this research focused on how memory and visual search are brought to bear on a task, future work could also study the contribution of spatial cognition in the DSST. Spatial regularity of the symbol-digit pairs was deliberately removed in the current research to focus on the contributions of associative memory and visual search. Additional research could determine how this spatial regularity improves performance.

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