Eyes Never Lie: Eye-Tracking Technology Reveals how Students Study Displays

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Abstract
This study investigated the achievement benefits of studying different forms of verbal displays and explored how students study these displays using eye-tracking technology. Sixty-eight college students were assigned randomly to one of four display groups: text, outline, simple matrix, and signaled matrix. One at a time, students wearing an eye-tracking apparatus studied their one-page display on a computer screen for 15 minutes in preparation for achievement tests that followed. Achievement results indicated that studying text displays produced lower achievement than studying any of the other displays. Unlike past studies, however, no advantage was found for matrix study over outline study perhaps because of design constraints associated with eye tracking. Eye-tracking results, however, were robust. Both quantitative and qualitative analyses showed that students tend to study text and outline displays one topic at a time, whereas students tend to study matrix displays across topics. Across-topic study is instrumental in spotting and learning comparative relationships among topics. Implications for research and practice were provided.

***Keywords**: matrix, verbal display, eye tracking*

Introduction

Suppose you had to study information on different species of wildcats in preparation for a test. Would it be better to study that information when it is displayed in text, outline, or matrix form (as shown in Figure 1)? Researchers have investigated which verbal display works best and confirmed that studying a matrix produces higher achievement than studying a text or outline (Kauffman & Kiewra, 2010; Kiewra, DuBois, Christian, & McShane, 1988; Kiewra, DuBois, Christian, McShane, Meyerhoffer, & Roskelley, 1991; Kiewra, Kauffman, Robinson, DuBois, & Staley, 1999). Such research is designed so that the three displays have informational equivalence—the same number of critical ideas—but vary in structure. Structurally, a text contains blocks of information in paragraph form, an outline contains lines of information in a list-like form, and a matrix contains smaller bits of information in table form. In one representative study (Kauffman & Kiewra, 2010), students studied longer and more detailed versions of the abbreviated wildcat material shown in Figure 1. They studied either a five-page text containing about 2000 words, a three-page outline containing about 400 words, or a one-page matrix containing about 250 words. Although word count differed, all three displays had informational equivalence and contained the same 78 facts about six species of wildcats. Results showed that matrix studiers achieved more than outline studiers who, in turn, achieved more than text studiers on both fact and relationship tests. In a similar study where word totals were equated for text, outline, and matrix displays, matrix study still produced higher achievement (Robinson et al., 2006).

Researchers have also theorized that matrices are superior to texts and outlines because they are built more efficiently. According to Kauffman and Kiewra (2010), and as shown in Table 1, three factors explain matrices' superior efficiency: signaling, extraction, and localization. Signaling refers to cues that aid information access. An outline's topic and subtopic organization and a matrix's column and row structure make it easy to access facts (e.g., the cheetah's weight is 125 pounds). A text does not commonly provide such signals. Extraction is the process of identifying the most important text information and setting it apart. Only outlines and matrices extract critical information and set it apart. Localization is the process of positioning related information in close proximity. All three displays have topical localization. They place information about a single topic (such as tigers) in the same text paragraph, the same outline section, or the same matrix column. Only the matrix, though, has categorical localization. Information about the "call" category, for example, appears across a single matrix row for easy viewing and comparison. That same information, though, appears in four different text paragraphs and four different outline sections. Categorical localization in the matrix makes finding comparative relationships across topics quick and easy. With just a glance at the matrix in Figure 1, for example, you see that wildcats with louder calls weigh more and live longer than wildcats with softer calls. In addition, you see that jungle cats are solitary, whereas plains cats live in groups. In conclusion, outlines are more efficient than texts because of better signaling and extraction, and matrices are more efficient than outlines because of better categorical localization.

Of course, a matrix's categorical advantages might only be realized if students study a matrix horizontally by category (at least to some degree). If they only study a matrix vertically by topic, then they might miss comparative relationships like those mentioned above. Using computer technology, an experiment was conducted to uncover how students should study a matrix in order to benefit from its categorical advantages (Jairam, Kiewra, Kauffman, & Zhao, 2012). In that experiment, students studied a matrix topically, with only one column appearing at a time; categorically, with only one row appearing at a time; or in a unified way, with the full matrix appearing at all times. Results showed that studying the matrix categorically, row by row, or in a unified way led to higher achievement on fact and relationship tests than studying the matrix topically, column by column. And, results from a supplemental experiment in that same study also showed that adding color-coded signals to the unified matrix resulted in increased relationship learning.

In summary, it has been established that (a) studying a matrix display increases achievement more than studying text or outline displays, (b) a matrix is more effective than other displays because it offers categorical localization of related ideas, and (c) studying a matrix horizontally by category is superior to studying it vertically by topic. What is unknown, however, is how students actually study a matrix when left to their own devices. Are they getting the most they can from their study?

Do they study a matrix column-by-column, row-by-row, or some combination of both? To find out how students study a matrix and other displays, the present study used eye-tracking technology to track the path of students' eye movements as they studied displays. The remainder of this introduction briefly describes eye-tracking theory, technology, and application before introducing the present study.

Eye tracking has been used as a measure of reading comprehension (e.g., Gordon, Hendrick, Johnson, & Lee, 2006; Rayner, 1998; Rayner, Chace, Slattery, & Ashby, 2006). According to the eye-mind theory (Duchowski, 2007), readers' eyes reveal not only their place in the text but their mental processing too. For example, a relatively longer fixation might mean that more attention is being paid to a difficult text section.

Eye-tracking systems use miniature cameras affixed to a band placed around the learner's head to record eye movements. Resulting data usually include number of fixations or times the eye focuses on areas of interest (or number of times that the eyes leave and return to areas of interest) within the learning materials, fixation duration or time spent looking at key words, and scan paths that show how learners' eyes move from spot to spot on their learning materials. A large number of fixations might suggest the importance of certain points that demand repeated fixations. Long fixations might reflect difficulty in understanding and interpreting (Hyona, 2010). And, scan paths might indicate the nature and efficiency of processing (Jacob & Karn, 2003).

To our knowledge, only two studies have used eye-tracking technology to investigate how verbal displays other than text are studied. In one study, Salmeron, Baccino, Canas, Madrid, and Fajardo (2009) used eye tracking to examine how giving students a hierarchical organizer in advance of reading easy or difficult texts affected their study. Participants had longer fixation times on the hierarchical organizer when the text was difficult than when it was easy. Moreover, longer fixation durations on the organizer led to higher test scores.

In another study, Liu, Chen, Chuang, and Huang (2012) used eye-tracking technology to assess the effectiveness of two types of advance organizers presented prior to the full text: question-based and summarized. Eye-tracking results showed that participants given the summarized organizer spent less time reading the organizer than reading the text. In contrast, participants given the question-based organizer spent more time reading the organizer than reading the text. The researchers concluded that summarized organizers were more efficient in aiding participants' reading comprehension compared to question-based organizers. One possible reason is that question-based organizers invited more active processing than summarized organizers, and thereby reduced the time available for reading the text that followed.

These two investigations (Liu, et al., 2012; Salmeron et al., 2009) are closest to our research interest because both track eye movements to examine what students look at while they study graphic organizers. Neither study, however, examined how students study various displays and the matrix display in particular. The purpose of the present study was to do just that.

In the present study, college students studied one of four displays (text, outline, simple matrix, or signaled matrix) in preparation for fact, relationship, and transfer tests. While they studied, an eye-tracking apparatus recorded their eye movements. In line with established matrix research and theory, we predicted that matrix groups would (a) achieve more and (b) scan their displays in more categorical ways than outline and text display groups.

Methodology

Participants and Design

Sixty-eight undergraduate students from the educational psychology research participant pool at a large Midwestern university participated to obtain research credit. Eight participants (12%) could not complete the study because the eye tracker could not track their eye movements. This percentage of non-tracked participants is considered normal (Jacob & Karn, 2003). Among the remaining participants, 93% were Caucasians, 73% were female, most were juniors (25%) and seniors (50%), and most (87%) held grade-point averages of 3.0 or higher. Participants were assigned randomly to one of the four verbal display groups: text (n = 14), outline (n = 14), simple matrix (n = 17), or signaled matrix (n = 15).

Apparatus

The EyeLink II computer-based eye-tracking system collected eye movement data. This system included a head-mounted eye tracker, a display computer, and a host computer. The eye tracker was comprised of two miniature cameras mounted on a padded headband worn by participants. The eye tracker captured participants' eye movements as they studied a verbal display presented on the display computer in front of them. The host computer, located in the adjoining room, recorded and stored eye movement data pertaining to eye fixation numbers, durations, and paths.

Materials

Materials included a demographic survey, study material about wildcats displayed in four different forms, a vocabulary test, and three achievement tests. The four wildcat displays were presented via computer; the other materials were paper-based. The demographic survey asked participants to declare their gender, ethnicity, class standing, overall GPA, and prior knowledge about wildcats.

There were four wildcat displays akin to those shown in Figure 1: text, outline, simple matrix, and signaled matrix (not shown in Figure 1). Wildcat material was used because it was used in previous display research that produced achievement differences (e.g., Jairam, et al., 2012). All contained equivalent information about six wildcat topics presented in the same order (tiger, lion, jaguar, leopard, cheetah, and bobcat) and nine categories presented in the same order (call, weight, life span, habitat, social behavior, range, time of hunt, distinct trait, and hunting method) for each topic. In all, there were 54 facts with each fact corresponding to the intersection of a wildcat topic and category. For example, the fact "tigers roar" stems from the topic of tiger and the category of call.

Although the four displays contained identical information, the displays' word counts and structures varied. The text display contained 1056 words and was divided into six paragraphs according to the six wildcat topics. An example text sentence was, "The jaguar's call is a growl." The outline display contained 198 words and was divided into six sections according to the six wildcat topics. Each section began with a wildcat's name and was followed by nine lines, each showing a category name and related fact. For example, under the Jaguar topic, the first line was, "Call: Growl". In order to fit all of the information onto one screen, the six outline sections were placed in two unaligned columns rather than in a single column like most outlines. This unaligned design was used so that category names (such as call) did not align across topics. Category alignment is the hallmark of matrices, not outlines. The 115-word simple matrix was a two-dimensional table that listed the six wildcats' names (topics) along the top row and the nine categories down the left-most column. The 54 matrix cells that intersected topics and categories each contained one fact. For example, at the intersection of jaguar and habitat was the single fact "jungle". The signaled matrix (see Jairam, et al., 2012) was identical to the simple matrix except that it was color-coded to signal relationships. For instance, the six wildcats' weights, calls, and lifespans were interrelated so all of this (and only this) information appeared in blue type. These matrix cells were also shaded in three colors to show the relationship that heavier weight cats have louder calls and longer lifespans than medium weight cats, which, in turn, have louder calls and longer lifespans than lighter weight cats.

The vocabulary test contained eight multiple-choice questions taken from the vocabulary portion of sample Scholastic Aptitude Test items. This test served as a filler task to clear participants' short-term memory between studying and testing and as an index of verbal ability.

Three achievement tests assessed fact, relationship, and transfer learning. The fact test contained 54 matching items organized by the nine wildcat categories. For example, the six items pertaining to the weight category required participants to match the six wildcat names to their six weights. The relationship test contained 26 short-answer items. Some items tapped relationships within a topic (e.g., How is the leopard's distinct trait related to its hunting method?), some tapped relationships within a category (e.g., What is the range of wildcat weights?), and some tapped relationships across multiple categories (e.g., What is the relationship between call and weight?). The transfer test measured participants' ability to apply the wildcat information to new settings. Participants were given information about "newly discovered" wildcats (e.g., This newly discovered wildcat was observed in the jungle and looked to weigh about 100 pounds) and asked to predict things like its range and hunting behavior.

Procedure

The study took place in the eye-tracking laboratory housed on the university campus. Because there was only one eye tracker available, data were collected one participant at a time, and all participants followed the same procedure. Upon arrival, participants were assigned randomly to one of the four display groups (text, outline, simple matrix, or signaled matrix). Each participant was then read the experimental instructions that revealed the experiment's purpose (to determine how students study instructional materials), four phases (pre-survey, eye-tracker adjustment, study session, and testing), and participant expectations (e.g., do as instructed throughout and try your best). Next, the pre-survey was completed. Then, the eye tracker was placed on the participant and calibrated. When calibration was completed, the participant tapped a designated key that presented the display material on the computer screen and started the eye-tracking process. Every three minutes, the study session was briefly interrupted for eye-tracker recalibration to ensure accurate data collection. During the 15-minute study session, the participant solely studied the material displayed on the computer screen. No other study materials or tools were available, and the participant was forbidden to take handwritten notes or to create another file on the computer to record notes. Meanwhile, a researcher was monitoring the entire process on the EyeLink II host computer in the adjoining control room.

Following the study session, the researcher re-entered the testing room and removed the eye tracker from the participant. Then, the participant was led to a quiet room to complete the vocabulary test (10 minutes), transfer test (5 minutes), relationship test (15 minutes), and fact test (10 minutes), in that order. The entire procedure took about 60 minutes per participant.

Results

Preliminary analyses were conducted on demographic variables and on vocabulary scores to ensure that the groups were comparable. The four display groups were comparable in terms of gender, ethnicity, class standing, GPA, wildcat prior knowledge, and verbal ability. The main analyses discussed next were conducted to detect differences in achievement and eye movement.

Achievement

A MANOVA was conducted to detect display group differences on transfer, relationship, and fact tests. There was a significant difference in test performance for the display groups, F (9, 132) = 2.00, p = .045; Wilk's Λ= .73, partial η^2 = .10. To determine how display groups differed on each test, between-subjects effects were examined. These analyses revealed group differences for the fact test only, F (3, 56) = 2.87, p = .04, η^2 = .13 (medium effect). Fisher's LSD post hoc tests indicated that the outline, simple matrix, and signaled matrix groups all learned significantly more facts than the text group. Table 2 shows the percentage means and standard deviations for all display groups across the three achievement tests.

Eye Movement

With respect to how participants studied displays, two measures of eye movement data were examined: run count and scan path. Run count indicated how often a participant's eyes moved away from an area of interest (AOI) and later moved back to this area again. The predetermined AOIs for this study were the six wildcat topics. Higher run counts would indicate that participants generally moved from topic to topic more often as they studied than did those with lower run counts who generally studied one topic at length before studying another. Because run count data were collected for each of the six AOIs, a total run count (TRC) was established for all interest areas. And, because recalibration was done every three minutes, five eye movement intervals (each three minutes long) were also established. Given these parameters, a factor analysis on TRC for display group and time interval effects was conducted. Results[1] revealed a main effect of display group, F (3, 250) = 39.5, $p < .00$, $\eta^2 = .32$ (large effect). Specifically, Tukey's HSD post hoc tests revealed that the two matrix display groups had significantly higher TRCs than the text and outline display groups ($p < .00$). There was also a main effect of time interval, F (4, 250) = 3.3, $p = .01$, $\eta^2 = .05$ (small effect). Tukey's HSD post hoc tests indicated that participants had marginally higher TRCs in Time Interval 1 than in Intervals 4 or 5 ($p = .05$ and .07, respectively). The interaction between display group and time interval was not significant. In summary, these run count findings suggested that the two matrix display groups compared information across topics more frequently than the text and outline display groups and that all display groups, in general, also did more comparisons at the beginning of the study period than towards the end. Table 3 presents the run count data, and Figure 2 illustrates the run count patterns.

The other eye movement measure, scan path, was a qualitative measure obtained by watching the complete replays of 20 participants' (5 chosen randomly from each group) eye movements on the computer screen. A researcher examining the replays classified each as (a) topical if participants largely scanned from one idea to another within a topic (e.g., tiger) and then from one topic to the succeeding topic (e.g., from tiger to lion), (b) categorical if participants largely scanned from one idea to another within the same category (e.g., call) and then from one category to another (e.g., from call to weight), and (c) random if participants largely scanned the screen with no discernable pattern. A second researcher independently watched one-third of the reply videos and summarized the scan patterns as well. The two researchers later compared their observations and reached agreement for each participant's scan path pattern.

Scan path results showed that the text display group tended to scan the material topically—top-to-bottom, paragraph-by-paragraph, and line-by-line. They essentially read and reread the text and made almost no attempt to integrate material between paragraphs (topics). For the outline display group, most participants scanned the material topically—topic-by-topic, from top to bottom, again and again. A few participants looked occasionally from topic to topic so that topic comparisons could be made. Participants in the simple matrix display group primarily scanned the matrix categorically. Right from the start, every participant scanned horizontally and across wildcat topics. This would permit them to discern horizontal relationships within categories such as call and weight. After a while, some participants also studied vertically, which would allow them to discern relationships within topics. Participants in the signaled matrix display group had scan paths much like those in the simple matrix display group. In addition, their eyes frequently moved from row to row, which would enable them to discern relationships that exist between multiple categories such as call and weight. Overall, the scan paths showed that the two matrix groups compared the information categorically across topics more than the other two groups. This finding is consistent with the quantitative run count data.

Discussion

The present study sought to reconfirm previous findings that studying a matrix display results in higher achievement than studying text or outline displays and to break new empirical ground by determining just how students study various displays, particularly the matrix. With respect to achievement, present findings reconfirmed that outline and matrix display groups learned more facts than the text display group. Surprisingly, however, the display groups did not differ with respect to relationship or transfer learning, and the expected achievement advantages of matrix study over outline study did not materialize for any learning outcome.

These unexpected findings might be the result of design factors unique to the present study. Because the present study used eye-tracking technology, it was necessary to fit each display on a single computer screen page without the need to scroll. This restriction resulted in text and outline displays that differed markedly from those used in past studies. Kauffman and Kiewra (2010), for example, used a wildcat text that appeared on five pages and was about 2,000 words long. The wildcat text in the present study appeared on one page and was only about 1,000 words long. The past study also used an outline that appeared over three pages, whereas the outline in the present study appeared on a single page. The text and outline displays used here were not only different from those used previously; they were, because of eye-tracking constraints, also designed in ways that violated their very nature to some degree. The present text was bare bones; it contained no extraneous information as most texts do. More importantly, it provided explicit signaling cues throughout. Rather than conversationally report, for example, that a cheetah makes a hissing sound or that it lives in groups, the present text drew readers' attention to the category names and associated facts by reporting information this way: "The cheetah's call is a hiss" and "It's social behavior is groups." As seen in Figure 1, texts commonly lack these clear signals ordinarily found in outlines and matrices. Meanwhile, the present outline was presented in two columns instead of its customary one column, which might have unintentionally invited and simplified across-topic comparisons among wildcats. In essence, because of its two-column design, the outline looked more like a matrix than an outline. Future research might replicate the present study using paper materials so that computer constraints do not compromise the materials' structure or the students' study methods.

Although the accommodations made to employ eye-tracking technology might have diminished achievement findings, such accommodations were worthwhile in producing original quantitative and qualitative data about how students study various displays, particularly the matrix. As predicted, run-count and scan path analyses showed that text and outline studiers tend to study in a linear fashion, one topic at a time, whereas matrix studiers tend to move from topic to topic so that they might better draw out the important categorical relationships that exist across topics (e.g., "most wildcats live in the jungle" or "the louder a wildcat's call the heavier its weight"). In this way, present findings reconfirmed matrices' categorical advantages (Jairam, et al., 2012).

Present findings also indicated that display studiers make more topic-to-topic eye movements earlier in the study period as opposed to later. A closer examination of Figure 2, however, suggests that most of the topic-to-topic study stems from the matrix display groups. And, although the matrix groups do somewhat less topic-to-topic study as time goes on, they continue to do more than the text and outline display groups throughout the study period. We are uncertain why participants studied in a more topic-to-topic fashion in the earlier study periods than in the later periods. Future research might add a follow-up interview or a think-loud procedure to uncover explanations.

Finally, the present study has implications for research and practice. Researchers should strive to measure eye movements using computer or paper displays that are more ecologically valid such as longer and less contrived texts and single column outlines that extend beyond a page. Researchers might also re-investigate signaled matrices to uncover ways they might increase achievement more than they did in the present study. Teachers and students should employ matrices more often for learning comparative material. Unlike texts and outlines, matrices encourage learners to study information by categories as well as by topics. Categorical study helps students see and learn important relationships across topics that might otherwise go unnoticed.

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Footnote

[1] Reduced sample size (n = 54) for eye movement data was the result of equipment malfunction that interrupted the data saving process.

Appendix

Table 1 : Efficiency Ratings for Three Types of Displays

		Display	
Efficiency	Text	Outline	Matrix
Signaling	No	Yes	Yes
Extraction	No	Yes	Yes
Localization	Topical	Topical	Topical Categorical
Overall	Low	Medium	High

Table 2: Test Score Percentages (and SD Percentages) for Display Groups

	Test Performance		
Display Groups	Fact	Relationship	Transfer
Text (*n*=14)	86 (15)	72 (18)	58 (33)
Outline (*n*=14)	94 (6)	82 (11)	77 (67)
Simple Matrix (*n*=17)	94 (9)	74 (16)	66 (32)
Signaled Matrix (*n*=15)	95 (7)	75 (17)	78 (25)
Total (*n* = 60)	92 (10)	75 (16)	70 (41)

Table 3 : Eye-tracking Run Counts (and Standard Deviations) for Display Groups at Five Time Intervals

	Time Interval				
Display Groups	1	2	3	4	5
Text (*n* = 14)	104 (53)	114 (50)	131 (49)	120 (38)	130 (49)
Outline (*n* = 14)	113 (38)	126 (36)	108 (36)	97 (41)	93 (42)
Simple Matrix (*n* = 14)	223 (75)	185 (61)	175 (71)	167 (58)	171 (52)
Signaled Matrix (*n* = 12)	230 (62)	194 (49)	189 (65)	170 (53)	162 (73)
Total (*n* = 54)	165 (82)	161 (56)	149 (64)	137 (56)	138 (61)

Figure 1: Text, outline, and matrix displays for abbreviated wildcat material.

Text

The tiger's call is a roar. Its weight is 450 pounds. Its lifespan is 25 years. Its habitat is the jungle. Its social behavior is solitary.

The lion's call is a roar. Its weight is 400 pounds. Its lifespan is 25 years. Its habitat is the plains. Its social behavior is groups.

The cheetah's call is a hiss. Its weight is 125 pounds. Its lifespan is 8 years. Its habitat is the plains. Its social behavior is groups.

The bobcat's call is a hiss. Its weight is 30 pounds. Its lifespan is 6 years. Its habitat is the jungle. Its social behavior is solitary.

Outline

Tiger
- Call: Roar
- Weight: 450 pounds
- Lifespan: 25 years
- Habitat: Jungle

Lion
- Call: Roar
- Weight: 400 pounds
- Lifespan: 25 years
- Habitat: Plains
- Social Behavior: Groups

Cheetah
- Call: Hiss
- Weight: 125 pounds
- Lifespan: 8 years
- Habitat: Plains
- Social Behavior: Groups

Bobcat
- Call: Hiss
- Weight: 30 pounds
- Lifespan: 6 years
- Habitat: Jungle
- Social Behavior: Solitary

Matrix

	Tiger	**Lion**	**Cheetah**	**Bobcat**
Call:	Roar	Roar	Hiss	Hiss
Weight:	450	400	125	30
Lifespan:	25	25	8	6
Habitat:	Jungle	Plains	Plains	Jungle
Social Behavior:	Solitary	Groups	Groups	Solitary

Figure 2: Eye-tracking run counts for display groups by time interval.