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Design of a Complex Process Information Visualization: A Study of Eye Tracking and its Relationship to Cognitive Learning

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Abstract
Given the prevalence of visual instruction, it is important to ascertain how these visuals enable cognition particularly while having the complexity of information visualization that encompasses multiple concepts. This study was conducted with fifty female undergraduate students in a university in the central region of Saudi Arabia. It sought to understand what pattern and process a viewer's eyes takes when viewing a complex design of instructional information visualization, and to ascertain if any correlation exists between eye movement, specifically frequent visits to an area of interest (AOI), and cognition. It builds on literature that identifies a link between patterns of viewing and thought to address whether, using new technology, evidence for such a link exists. It also builds on studies that emphasise the importance of eye tracking technology to test hypotheses concerning perceptual processing. The study employs quantitative analysis to answer the research question. The study reveals that no significant correlation exists between a participant's eye movement and their degree of cognition associated with the material being observed. Recommendations for a further qualitative study are provided in order to clarify the relationship between eye movement, when focused on a complex design of information visualization, and cognitive uptake.
Keywords: instructional design, visual instruction, eye tracking, complex instructional information visualization

1. Background

The context of learning often includes complex visual resources. It is important to understand how such resources affect cognition given their prevalence in education. Several studies have examined the effects of cognitive load theory (CLT) on the processing of complex visual information, including investigating the relationship between cognitive load theory and eye tracking data. They have included analyses of fixation duration, fixation time, and the number of visits to an area of interest (AOI). CLT maintains that it is only possible for an individual to process a certain amount of information at any given time and, once this limit has been reached or exceeded, it is very difficult for the learner to focus on the information given (Sweller 1988). CLT is useful in facilitating an understanding of the limitations of learners' cognitive capacities (Mayer & Moreno 2003). Just & Carpenter (1976a, 1976b) establish a link between elements of eye fixation behaviour (including locus, duration and sequence) and argue that there is a strong correlation between where a subject is looking and his or her thought processes. Tufte (1983) formulated what he considered to be an optimal layout for the display of complex data. Mayer (2010) has emphasised the importance of studies focused on the relationship between CLT and eye tracking data, stating that "eye tracking measures, such as total fixation time on relevant areas of instructional graphics, can be successfully added to researchers' toolboxes as a way of testing hypotheses about perceptual processing during learning under different instructional methods." (p.169) Researchers Boucheix and Lowe, and De Koning, Tabbers, Rekers and Paas (2010) sought to determine the effect of visual cues on cognition in complex instructional animations. Both studies found that learners spend more time looking at relevant areas of an animation when visual cues are given and that this improved cognition. In another study, Jarodzka et al. (2010) found that subject experts spent more time looking at relevant areas of a visual stimulus, whereas novices would be easily distracted by non-relevant aspects. They discovered a strong link between eye-fixation and cognition. Furthermore, Canham and Hegarty (2010) found that students who had just attended a lecture on wind movement were able to process visual data, in order to infer wind direction, more accurately from a map illustrating only barometrical pressure, than from a map containing non-relevant temperature data. Using eye tracking methodology they too ascertained a strong link between eye-fixation and cognition. More recently Eckstein et. al. (2016) have reviewed eye tracking measures as a way of ascertaining cognitive development and plasticity; Was et. al. (2016) have investigated recurrent eye behaviours in a computerised mathematics activity, and Watson (2016) investigated the feasibility of using eye tracking technology to operate a robot remotely during a visual search task. And Scheiter and van Gog (2009) have argued that, in media design, elaborated theories exist that specify how instructional or informational multi-representational materials should be designed so that information processing can be optimally aligned with a user's cognitive resources. Kim et al (2012) established, through eye-tracking data, that visualization techniques are effective in promoting quicker decisions among research participants. While Prasse (2011) found eye-tracking data to be effective in understanding how research participants process the results of an initial web search, in order to select the items for further investigation. The study found that "visit count" was a widely overlooked metric, and was a more effective way of evaluating the significance of an AOI than visit duration.

The prevalence of such studies clearly shows that eye tracking techniques are an effective means of ascertaining how complex visual information is processed. By providing valuable information on the type of visual stimuli the learner's attention is drawn to, correlated with the information the learner is processing, research has shown that certain stimuli are now known to likely cause a high cognitive load and be too demanding for the learner. As a consequence, research in this area is useful for recommending how the design of visual resources can be best optimised to facilitate improved cognition. While the studies listed above used eye tracking data related to eye-fixation on AOIs to corroborate their findings, more information is needed to determine how complex visual resources can be adapted to suit individual learning needs. One such lack is the question of what the significance of the number of visits to an AOI is when viewing a complex visual. Is there, for example, a correlation between the frequency of visits to an AOI and cognition? Does a high frequency of visits to an AOI signal a deeper engagement with the material, or a difficulty in comprehension? And can a higher number of visit predict a deeper understanding? This study aimed to address these question through examining student's attention while perceiving complex visual resources using eye tracking technology. The study focused on students with a range of learning proficiencies, matching their cognition against the number of visits they made to the AOIs.

The findings contained within this study help to broaden the understanding of both visual learning and CLT, including providing instructional designers with greater means to design information visualization systems that can adapt to the needs of learners (Tufte, 1983; Lohr, 2008 and Morrison et al, 2011). This study also helps to address underlying factors that might hinder cognition of visual resources. By designing resources that will prevent learners from becoming overwhelmed or losing their focus, a pedagogical efficiency can be supported through a dynamic relationship between instructional design and learning outcomes. The findings within this study have implications for the application of instructional design in areas inside and outside the field of education. This includes the increasingly visual and virtual space of modern combat, public service instructions, and other areas in which visual instruction is central to the effective performance of critical processes.

2. Methods

2.1. Design

The study aimed to answer the following research questions: does a high frequency of visits to an AOI signal a deeper engagement with the material, or a difficulty in comprehension? And can a higher number of visits to an AOI predict a deeper understanding? This study followed a quantitative methodology to answer the research questions. Person Correlation coefficient analysis and point biserial were conducted to examine the relationship between the independent variable (eye fixation measure) and the dependent variable (learner's performance). In addition, simple regression analysis was performed to determine whether a higher number of visits to an AOI predicts achievement. The complex graph used in this study includes two AOI: right and left (see figure 1). A subjective performance test was used to assess the learner's cognitive process (De Koning et al 2010). One question was asked for each selected area in the graph (right and left AOI) to test participants' achievement. In doing so the study was able to ascertain whether a relationship exists between the number of visit on AOI and achievement, and whether a relationship exists between either the right or left AOI and achievement.

2.2. Participants

Fifty female undergraduate students participated in the study, with a convenience sample. Each took part in the test through observing a complex visual design. The study was conducted in a university in the central region of Saudi Arabia.

2.3. Procedures

Each participant was tested individually in a single session. Before being asked to observe the complex information visualization material, participants were given individual instruction as to the requirements of the study and were informed that they would be given a test after the session to assess their learning. Each participant's eye movement was automatically calibrated by tobii x120. Poor calibration has been removed to assure the quality of the data.

3. Results and conclusions:

The main goal of the study was to investigate whether a high frequency of visits to an AOI signals a deeper engagement with the material. The data collected for the variables (number of visits for right and left AOI and achievement scores) was used to answer the research questions. To find the relationship between the number of visits to an AOI and achievement, a correlation coefficient analysis (Pearson) was conducted. The correlation coefficient of (0.180, $p = 0.211$) indicates a weak correlation between the visit count and cognitive achievement at the level 0.05. This shows no strong link between the number of visits to AOIs and learning outcomes. In addition, point biserial analysis was conducted to find the relationship between visit count (left) and test 1 as well as the relationship between visit count (right) and test 2. No significant relationship was found between the variables AOI (left) and performance for Q1 (r = 0.224, p = 0.118) at the level 0.05. Also, no significant relationship was found between the variables AOI (right) and performance for Q2 (r = -0.095, p = 0.512) at the level 0.05. This implies that the frequency of visits to an AOI might not be as significant as hypothesised, bearing little relation to either positive or negative learning outcomes (see table 1).

Table 1. Data Analysis of Frequency of Visits to an AOI

variable		Performance
Visit count on AOI (Right)	Point biserial	-0.095
Visit count on AOI (Left)	Point biserial	0.224
Total visit on AOI (Right & left)	Person	0.180

In addition, R square also indicates a low score at $R^{2=}$ .032. The weak relationship between the number of visits to an AOI and cognitive performance indicate that certain patterns of eye behavior do not translate to either a high or low cognitive performance. Therefore, one cannot predict a performance from a higher number of visit to an AOI.

Table 2 shows the descriptive statistics of the variables. The mean visit score for the right AOI was 13 and the mean visit score for the left AOI was 15. However, the lowest visit score was 3 in the left AOI and the highest was 59 visits. On the other hand, the lowest visit score for the right AOI was 4 and the highest was 56 visits. That shows a similarity between the number of visits to both AOIs (right and left).

Moreover, the finding of participants' fixation measures shows variations of fixation count (see figure 2). Figure 2 shows the number of visits to AOIs of two participants. Participant A shows a higher number of visits to AOIs than participant B. The data clearly shows that participants have different styles of studying the graph. This particular variation may have significantly affected the finding of the study.

Table 2. Descriptive Statistics for the Variables

variable	n	Mean	Std. Deviation
Visit count on AOI (right)	50	13.5	8.859
Visit count on AOI (left)	50	15.5	11.641
Test 1	50	56	.501
Test 2	50	26	.443

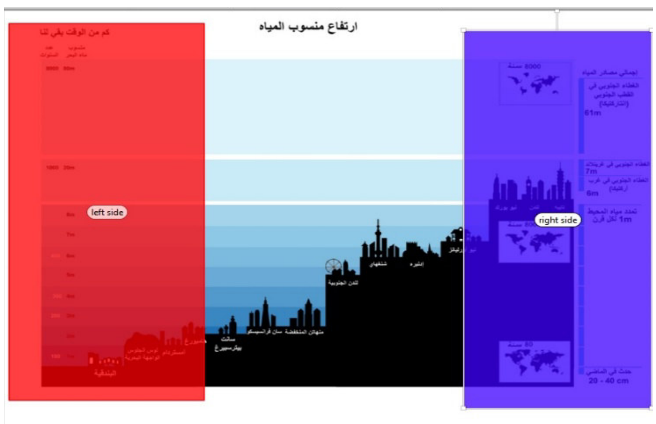

Figure 1. Area of Interest (left and right)

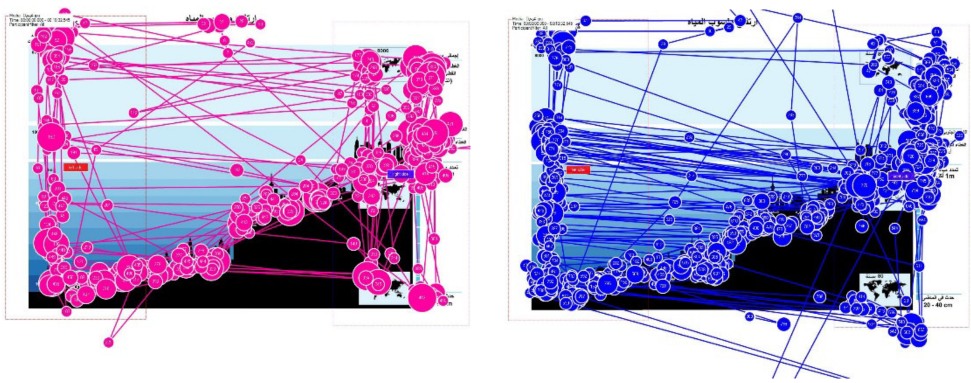

Figure 2. Participants' Viewing Patterns

The finding of this study is consistent with some previous studies which have shown that an individual's scan path can be affected by many factors, with eye behavior often idiosyncratic to an individual. This behavior can include scanning, comparing and contrasting. For example, Altonen et al. (1998) found that a scan path direction, such as top-down or bottom-up, can indicate a participant's search strategy. Additionally, Goldberg & Kotval (1999) found that deviation from a "normal" scan path can indicate search problems due to lack of user training or a bad interface layout.

In addition the findings of the study could be affected by other factors, including the complexity of the graph which may require more effort and time from the participants, and different patterns of viewing. The graph also shows that the information on the edge of the graph forming the U shape is regularly visited. Thus the design of the graph might also have increased visits to some areas that, in turn, led to a poor cognitive uptake. A further study is therefore needed to investigate the relationship between the number of visits and cognitive performance in different designs. Moreover, a further qualitative study is needed to investigate viewing patterns on a complex graph, and to enable an in-depth understanding of the phenomena that goes beyond the data and capabilities of this study. Such a study will help clarify the relationship between eye movement, when focused on a visual design for learning, and cognitive uptake. At present no such study has been conducted and, as the results from the current study are inconclusive regarding the relationship between these two variables, a further qualitative study is of particular urgency in order for this question to be fully addressed.

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