Visual Navigation Patterns and Cognitive Load

Laurel A. King

Communication and Information Sciences, University of Hawaii at Manoa
1680 East-West Road, POST 317, Honolulu, HI 96822
laurel.king@hawaii.edu

Abstract. Eye tracking technology is a prospective tool for augmenting cognition in real-time in response to screen navigation and other eye movements that can be monitored. This paper examines eye movements associated with differences in problem complexity. The experiment utilized constraint satisfaction problems of differing difficulty measured by the number of steps necessary to complete and the relative time required to solve it. Participants were observed and tested through an eye-tracking experiment to see if correlations between visual navigation and problem complexity were present. Eye movement patterns, in particular pupil size, have been used to measure cognitive load in other contexts [6-9]. The results showed overall increases in fixations and pupil size that corresponded to increases in problem complexity.

Keywords: Cognitive load, eye tracking, analytical reasoning.

1 Introduction

This paper explores the consequences of different levels of complexity on screen navigation during problem-solving tasks. Participants were observed and tested through an eye-tracking experiment to determine whether correlations between visual navigation and problem complexity could be detected and measured. In addition, individual differences in domain expertise, short-term memory, spatial ability, cognitive style and learning preference, which are thought to affect internal and external problem representation and comprehension of prepared external representations of problems, were measured [1-5] for possible affect as well. Eye movement patterns, in particular pupil size, have been used to measure cognitive load in other contexts [6-9]. If differences in visual navigation and other measures such as the duration and location of fixations and changes in pupil size can be observed using eye tracking, these differences can be used to augment cognition or customize views appropriately as eye tracking and other monitoring devices improve. Changes in pupil size are easier to track with eye tracking cameras because calibration is not required.

To better understand how increases in cognitive load due to an increase in task difficulty are present in the visual process and the strategy of the individual, the following question was considered. Do different eye tracking patterns occur for different levels of complexity in analytical reasoning? This was examined within subject as well as between subjects to see if measurable trends exist that could be used to augment cognition and lessen cognitive overload for a specific user. This would be

D.D. Schmorrow et al. (Eds.): Augmented Cognition, HCII 2009, LNAI 5638, pp. 254–259, 2009.

particularly important for kiosks and computers in schools and public places that are used by people of varying levels of expertise.

In order to measure changes related to increased cognitive load, eye movements were tracked as participants attempted to find a missing entry on a series of five simple 2x2 sudoku puzzles. The placement of the missing entry ranged in difficulty by the number of entries that must be remembered in order to deduce the missing entry. The goal was to see if changes in visual process corresponding to changes in complexity could be detected from eye movement patterns within subjects.

Problem complexity was defined in two basic ways in the study. Initially, problems were ranked for complexity according to the number of steps necessary to solve them. All of the problems were constraint satisfaction problems and grouped according to this definition of difficulty. The second measure of difficulty was calculated by the actual time taken to complete the problem and they were ranked accordingly. This method allowed for each participant to have his or her own unique ranking, but problems were also averaged over all participants to give an overall difficulty ranking based on duration. These rankings were used to compare visual navigation of similar problem types based on these two measures of difficulty.

Measuring and understanding differences that correlate to changes in complexity during problem solving can further our understanding of how representations can be customized to improve problem solving and recognize cognitive load for individuals and groups. The ability to identify cognitive load levels using a passive monitoring technique or sensors would benefit interface design and artificial intelligence in a variety of fields including education and business.

2 Previous Research

Cognitive overload presents problems for users as well as learners. As problem complexity increases, adequate problem representation becomes very important and often determines how successful the person will be in solving a problem [1, 2]. Jonasson states that qualitative representation of a problem prior to the quantitative solution indicates deeper conceptual understanding of the problem, whereas attempting to apply formulas without a qualitative and structural understanding of the problem is less effective and typical of novices[3]. Differences in visual navigation can indicate whether the problem solver is using a strategy that indicates structural understanding of the problem, leading to lower cognitive load from more efficient visual navigation and problem solving. Also, when problems require collaborative and interdisciplinary solutions, successful communication of a problem representation grows in importance [4, 5]. This research can also lead to better understanding of the effectiveness of representations for visual communication. If cognitive overload can be measured automatically, the information can be used to mitigate this through various techniques such as scaffolding, multiple problem representation, worked problems, etc.

Eye tracking represents a promising technique for measuring cognitive load. It is thought that fixation duration is a measure of difficulty of information extraction and interpretation; while the number of fixations in a region indicates level of interest [6]. The pupil size can also indicate things about the viewer and level of cognitive activity. Eye movements and changes in pupil size can reveal whether a person is experiencing cognitive overload [7]. Kahneman's theory of attention is partially based on the relationship between cognitive activity and pupil dilation [8]. Differences in pupillary response is seen as the most promising physiological indicator of cognitive load, although it may be less reliable for older users [9]. This methodology was further investigated using *sudoku* puzzles, which are examples of diagrammatic constraint satisfaction problems. Since they require no reading to complete, they are useful for measuring cognitive load in diagrammatic contexts, yet the semantics and rules are very simple and easy to remember.

3 Methodology

Eye movements were tracked and analyzed as seven university students completed a series of five simple *sudoku* analytical problems of varying complexity. The participants were also tested for other individual differences related to diagrammatic communication and reasoning, such as working memory capacity, visual and verbal preferences for learning and thinking, and spatial ability. This information was used to analyze possible correlations between these factors, strategies used, and indications of resulting cognitive load.

The goal of the study was to see if changes in cognitive load corresponding to problem complexity could be observed and recognized in eye movement patterns. This was analyzed quantitatively in terms of changes in pupil size and the number and duration of eye fixations. It was also analyzed qualitatively in terms of navigation patterns and the strategy used to solve problems. These were examined to understand the different solution strategies used and how the level of cognitive load impacted the strategy or process within and between subjects.

The following set of hypotheses was used to test for changes in eye-movements and pupil size correlating to differences in problem difficulty. The participants completed one practice *sudoku* problem and five *sudoku* problems of varying difficulty. Difficulty was measured in terms of the number of steps that must be remembered in order to find the correct solution. Problems increased in difficulty level according to the number of steps required to solve it. This was used to see if corresponding differences in the number of fixations, duration of fixations, average fixation, and average pupil size could be measured. These differences were also evaluated in terms of the other independent variables, such as the visual-verbal factors from the questionnaire, the spatial test and memory test scores.

Ha: Participants will have more eye fixations while solving higher difficulty problems than lower difficulty problems.

Hb: Participants will have longer duration of eye fixations while solving higher difficulty problems than lower difficulty problems.

Hc: Participants will have higher average pupil sizes while solving higher difficulty problems than lower difficulty problems.

Participants completed constraint satisfaction problems using a computer while their time per screen, fixation locations and durations, pupil size, and answers to problems were recorded using EventStream software and an ASL eye tracker. Their eye movements were tracked sixty times per second. The information from EventStream on the task completion times, answers to problems, and fixation locations, durations of fixations by area of screen, and pupil size from the eye tracker was coded by participant and kept in spreadsheets for further processing. The data included the response time, accuracy, pupil size, the number of fixations and gazes on different parts of the display for each problem. A qualitative analysis was done to understand the participant's strategy and use of the graphic representation in relation to accuracy and response time.

All problems were designed to be solvable while viewing a computer screen without additional notes or calculations, although for increased difficulty some required more working memory capacity than others.

4 Results

The eye movements showed trends for increased fixations, longer fixation durations, and increased pupil size as complexity increased. Figure 1 shows the increase in fixations as the problem difficulty increases. Despite individual differences in the number of fixations, an overall trend of the average of all subjects shows an increase as problem difficulty increased. Figure 2 highlights the increased average fixation duration as complexity increased. Although less pronounced, the tendency is for the duration of fixation to increase with problem complexity. Figure 3 shows the change in average pupil size for the problems as they increased in complexity. Pupil size is measured using a raw data coding to show the relative changes, but since each participant sat at

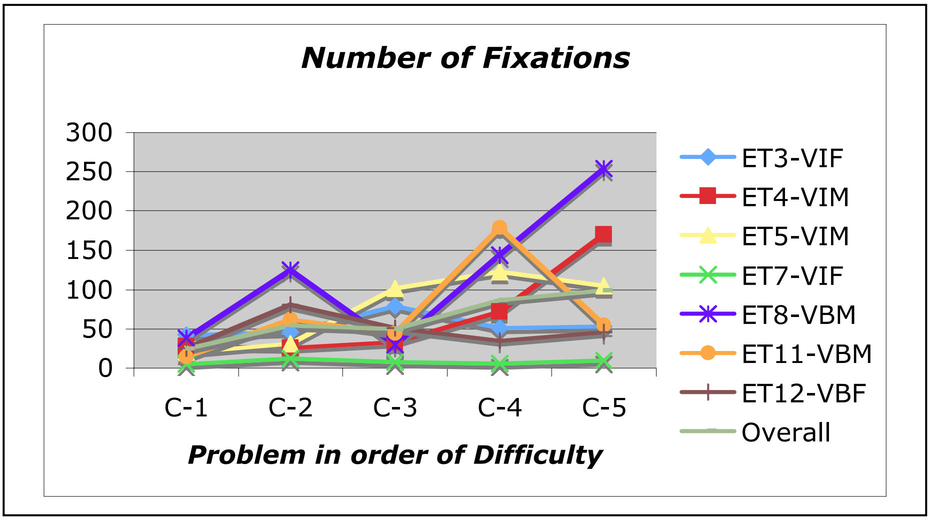

Fig. 1. Number of fixations per subject as problem difficulty increased

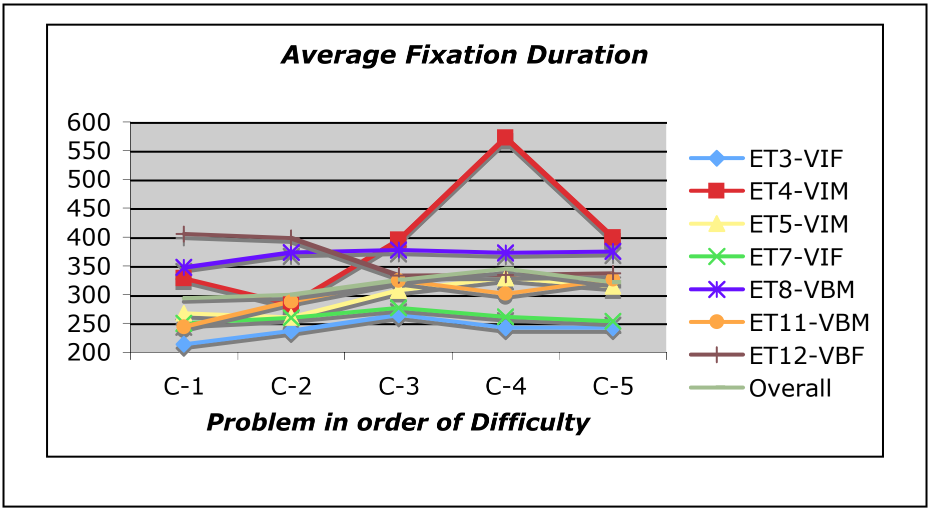

Fig. 2. Average fixation duration per subject as problem difficulty increased

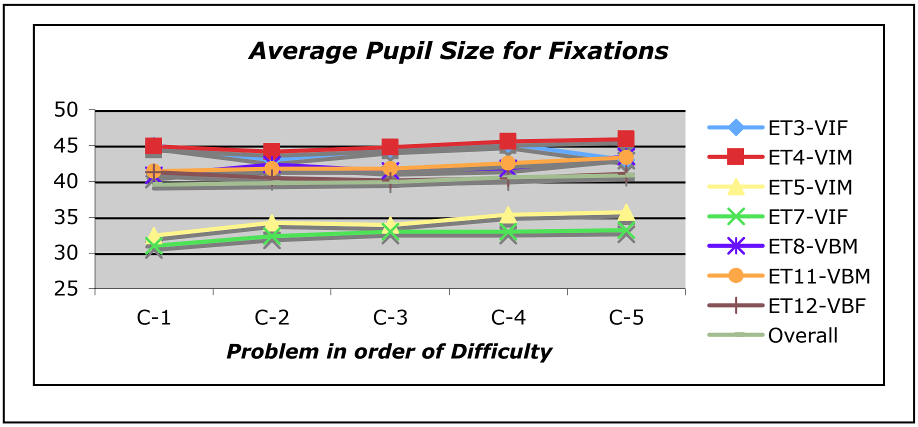

Fig. 3. Average pupil size per subject as problem difficulty increased

slightly different distance from the screen, it does not represent an exact measurement in millimeters.

Although, the change in average pupil size is small, there is a consistent upward trend for all subjects as the problem difficulty increased. The average was based on the pupil size averaged for each fixation. The blinks which caused the pupil size to be measured as zero were not used in the calculation. The wider range in pupil size seemed to be a better indicator of cognitive load than the average size.

The pupil size fluctuated throughout the problem solving tasks. The standard deviation increased as the difficulty increased as well, but the relationship was much noisier. Qualitative examination of the video of the eye movements and the pupil size seemed to indicate that the pupil size increased in connection with increased search behavior. However, this relationship is still being researched for a more specific and linkage. Intuitively, reacting to increased cognitive demand by increased search for relevant information seems plausible.

The three hypotheses were supported by the trends in the sample. The differences were not great, but there was a consistent increase in the average pupil size as well as the gap between the minimum and maximum pupil size. Eye tracking, in particular, changes in pupil size, may be feasible for detecting increases in cognitive load for augmenting cognition or determining performance level remotely.

5 Conclusion

Results showed that increases in cognitive load due to an increase in task difficulty were observed in the visual process and strategy of most participants. There is support for different eye tracking patterns to occur under increased complexity. This phenomena was examined within-subjects to see if measurable trends existed that could be used to augment cognition for a specific user during a visual task that requires reasoning. This type of user modeling and detection of cognitive load could be particularly useful for systems and interfaces that are used by people of varying levels of expertise, such as in schools and other public places.

Further research is underway to better understand how this and other visual indicators can be used to augment cognition and improve user experience with information and communication technology. Pupil size changes have potential for use in usability testing as well. Since tracking pupil size requires less calibration and is easier to do than eye movement tracking, it has potential for use with Web cameras that have become ubiquitous with Web 2.0 technologies.

References

1. Greeno, J.G.: Process of understanding in problem solving. In: Castellan, N.J., Pisoni, D.B., Potts, G.R. (eds.) Cognitive theory, vol. 2, pp. 43–83. Erlbaum, Hillsdale (1977)
2. Novick, L.R., Bassok, M.: Problem Solving, ch. 14. In: Holyoak, K.J., Morrison, R.G. (eds.) The Cambridge Handbook or Thinking and Reasoning, pp. 321–350. Cambridge University Press, Cambridge (2005)
3. Jonassen, D.: Using cognitive tools to represent problems. Journal of Research on Technology Education 35, 362–381 (2003)
4. Narayanan, N.H.: Technical Report CSE97-06: Diagrammatic Communication: A Taxonomic Overview. Auburn University (1997)
5. Van Bruggen, J.M., Kirschner, P.A.: Designing external representations to support solving wicked problems. In: Andriessen, J., Baker, M., Suthers, D. (eds.) Arguing to Learn: Confronting cognitions in computer-supported collaborative learning environments, vol. 1, pp. 177–203. Kluwer Academic Publishers, Norwell (2003)
6. Fitts, P.M., Jones, R.E., Milton, J.L.: Eye movements of aircraft pilots during instrument-landing approaches. Aeronautical Engineering Review 9, 24–29 (1950)
7. Marshall, S.P.: The Index of Cognitive Activity: Measuring cognitive workload. In: Proceedings IEEE 7th Conference on Human Factors and Power Plants, pp. 7.5–7.9. IEEE, New York (2002)
8. Kahneman, D.: Attention and effort. Prentice-Hall, Englewood Cliffs (1973)
9. Van Gerven, P.W.M., Paas, F.G.W.C., Van Merrienboer, J.J.G., Schmidt, H.G.: Cognitive load theory and aging: effects of worked examples on training efficiency. Learning and Instruction 12, 87–105 (2002)