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Exploring the Difficulties in Digital Logic Circuit Reading Comprehension via Saccade Analysis

Hong-Fa HO
Department of Applied Electronics Technology, National Taiwan Normal University, Taiwan, R.O.C.
*jackho@ntnu.edu.tw

Abstract: The purpose of this paper is to explore whether there are differences in the reading process between high-grade and low-grade students by tasking them to find a bug in a digital logic circuit. Based on the pre-test scores, 155 high school students were divided into a high-grade group and a low-grade group. To examine their reading process, both groups were asked to find a bug in a digital circuit, and an infrared eye tracker recorded their eye movement. Correlation coefficient was used to analyze the saccadic data. The findings show 1) the integrative saccades from signal names of the timing diagram to other Regions of Interest (ROI) has the lowest correlation coefficient (0.3345); 2) there is a larger difference in the integrative saccades between the high and low-grade groups from signal names of timing diagram to timing diagram ROIs of RESET, CLOCK, INPUT and OUTPUT. These findings show that the low-grade group had some difficulties in reading comprehension when reading timing diagrams of RESET and OUTPUT, but fewer difficulties when reading CLOCK and INPUT. In addition, difficulties in reading comprehension also appeared when calculating OUTPUT. This paper contributes to the field of learning science by providing evidence of the saccade difference between digital circuit readers with and without difficulties in reading comprehension.

Keywords: eye movement, reading process, digital logic circuit, saccade

1. Introduction

One of the basic skills of an electronics engineer is to read digital logic circuits (digital circuit in short) (Harris & Harris, 2012). Since many students have difficulties in reading digital circuits, understanding the reason for these difficulties is a key point in the electronics education.

A “saccade” is the eye movement people make when reading, viewing, or searching. The short pauses between saccades are “fixations”, and the brain obtains information during these fixations (Rayner, 1998). Fixations and saccades are common behavioral variables of eye movements.

Integrative saccades have been used to present referential connections between text and illustration. Holsanova, Holmberg, and Holmqvist (2009) adopted the concept of integrative saccades to represent verbal and pictorial information that correspond with each other. The referential connections variable can be used to represent the referential connection between two different types of pictorial information as well.

Digital circuits generally include circuit symbols, signal names of circuit, signals of circuit and wires (Kumar, 2009). For the convenience of reading, function tables and truth tables are often provided in circuit diagrams. Timing diagrams with various signals are also provided as well. Figure 1 is the experiment material used in this study and an example of a digital logic circuit.

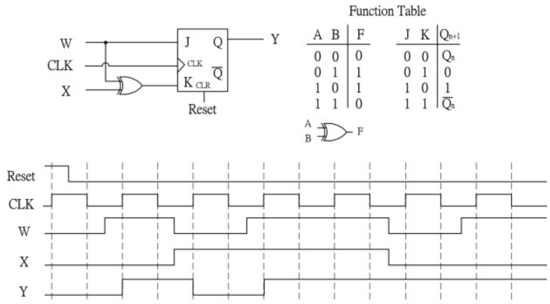

Figure 1.The digital logic circuit.

Most studies discussed the pedagogical issues surrounding digital logic (Reis & Marques, 2013), but none investigated the difficulties in reading comprehension of digital circuits. This study used an errorless circuit diagram (with function table and truth table) and a timing diagram with an embedded bug for the participants to read. The participants were required to find the bug, but did not need to give an answer of the correct waveform. Participants needed to go through a reading process to understand the digital circuit and find the bug. To understand the comprehension difficulty in finding the bug, this study used eye trackers to record participants' eye movements.

1.1 Research Question and Hypothesis

Since the linear reading style with continuous symbols of the text does not apply to the reading style of pictorial digital circuits, the author was curious whether there were variations in the reading style of digital circuits as well.

Q_1: Is there a difference in saccades between the high and low-grade group in the digital circuit reading process?

The logic saccade varies from person to person when difficulty in reading comprehension appears. Since the high-grade group had less comprehension difficulties than the low-grade group, the logic saccade between the two groups might be predicted to be different.

H_1: There is a difference between the saccade of high and low-grade groups in the digital logic circuits reading process.

2. Method

2.1 Participants

One hundred and fifty-five third grade students (N=155), who were aged from 17 to19 (average 18.37 years old), from the Department of Information Technology, Hsinchu Kuang-Fu Senior High School participated in a pre-test before the experiment. They consisted of 145 male and 10 female students. They all took digit electronic circuits course, and their average grade were above 60 (full score 100). Participants with high myopic and those who did not want to participate the experiment were excluded. The high-grade group and the low-grade group were selected based on the results of the pre-test; both groups had 40 students each. One of the 80 candidates did not complete the eye tracker calibration due to eye injury, and another did not complete calibration because she wore fashion contact lenses. Four of the candidates had invalid eye movement data. Since the eye tracker was mounted on the frame of a pair of glasses, participants with a higher degree of myopia could not wear their own glasses during the experiment. Seven candidates with medium-degree myopic were removed from the samples because they could not read the questions clearly. Thirteen candidates were screened out from the samples in the end. The number of effective sample was 67 (62 males and 5 females), including 32 high-score participants (N_1=32) and 35 low-scored participants (N_2=35).

Hence, the remaining 67 students who were computer literate and had normal or corrected to normal vision participated in the formal experiment. All participants signed written agreement for participating in this experiment. The participants were notified by a written statement that the aim of this experiment was to study their reading process.

2.2 Materials

This study designed a paper pre-test and a visual test. The pre-test was a paper test of 10 multiple-choice questions, 6 fill-in-the-blank questions and 4 questions of drawing timing diagram. The full score was 100 and the time limit was 45 minutes. The author graded the pre-test, and then illustrated the test results and the reliability (Cronbach's α=0.73) of the test.

The material of the visual test is illustrated in Figure 1. This question was designed to examine the reader's ability to read, comprehend, reason, and debug digital circuits. The knowledge and symbols tested were J-K flip-flop, level-triggering, XOR gate, function table, truth table, CLOCK, RESET and timing diagram. To eliminate the memory variable, the question included a function table and a truth table. The visual test was a debugging task, and a bug was embedded in the timing diagram.

In order to analyze the eye movement data, Regions of Interest (ROI) were allocated in the examination material. Table 1 shows the definitions of the ROIs in the experiment. Apart from the wires, the ROIs cover all the symbols and information in the examination material. Since participants did not have any problems in reading wires, wires and signal names were combined into one ROI instead of having separate ROIs. As shown in Figure 2, the visual test was divided into 58 ROIs for a more detailed analysis. The reading process could be analyzed in detail if a signal of the timing diagram was defined as multiple ROIs of the same category. For example, the ROI of CLOCK in Figure 2 is composed from no. 21~35 ROIs in the timing diagram, but these 15 ROIs all belong to R_6 of Table 1. The area in which the participants gazed at could be observed from the analysis of the eye movement data. The bug was embedded in no. 58 ROI of R_9.

Table 1: Definitions of different Regions of Interest (ROI) of the digital circuit.

ROI types	
R_1	function table & truth table
R_2	signals of circuit
R_3	signal names of circuit
R_4	signal names of timing diagram
R_5	RESET signal of timing diagram
R_6	CLOCK signal of timing diagram
R_7	input W of timing diagram
R_8	input X of timing diagram
R_9	output Y of timing diagram

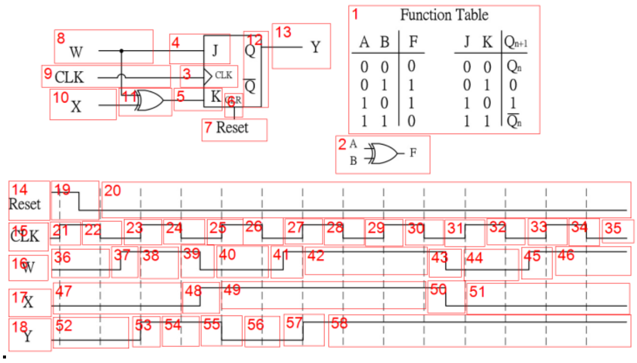

Figure 2.The ROIs of digital logic circuit

2.3 Design

This experiment was designed based on the pilot study. The participants had fast saccades and did not gaze at every symbol and line. Instead, they fixated briefly on certain symbols, timing diagram, and other objects. The visual information received was more stable when the participants gazed at particular areas during the reading process. The participants spent longer time processing the information while they were gazing at the diagrams, and their eye movement data reflected the symbols, timing diagram, and other objects that were being gazed or re-gazed. Logic forward fixations were shown when the participants did not have difficulties in reading, while logic regressive fixations were shown vice versa. When participants encountered difficulties in reading comprehension, they would reread symbols, timing diagram and other objects, and then integrate the information to help them understand the diagram.

This study was a 2 × 9 factorial quasi-experimental design. The first independent variable was the groups (the high-grade group and the low-grade group). The second independent variable was the nine ROI types defined in Table 1. The dependent variable was the percentage of the number of saccades starting from a ROI to another ROI in Table 1. In this study, the percentage of the number of saccades was referred to as integrative saccades. Integrative saccades represent the referential connection between two different ROI's information in a logic circuit. The hypothesis was verified by analyzing the integrative saccades in the nine ROIs of the participants' reading behavior.

2.4 Apparatus

The EyeNTNU-180 eye-tracking system which consisted of a glasses frame, a mini camera, two infrared LEDs and a laptop computer (P4-2.2 GHz) was used in this study. The stimuli, namely the question, were presented by this computer which also controlled the experiment. The computer had a 15.6-inch screen, and the reported angle-error of accuracy of the EyeNTNU-180 was 0.33°. A chin frame was used to increase the accuracy of measurement and stop the participants' head from shaking. The participants' eyes and the screen were 60 centimeters apart. The sampling rate of eye movement data was 180Hz. Eye movement data analysis software, ROI Splitter, Hot Zone Analyzer, Fixation Calculator and Saccade Statistics were used for analyzing eye movement data. SPSS for Windows of version 18.0 was used to analysis correlation coefficients.

2.5 Procedure

Pilot studies were conducted and modified prior to the formal group test and visual test.

All participants (N=155) took paper test for 45 minutes, and the author graded the examination paper. Based on the results of the pre-test, the author selected 40 high score and 40 low score students. 32 participants in the high-grade group and 35 participants in the low-grade group participated in the visual test after the elimination of vision problems.

The procedure was illustrated to the participants before the experiment. The mini camera was adjusted and a nine-point calibration was conducted. A sample of a circuit diagram and a timing diagram were given to the participants so that they could familiarize with the question type and the experimental procedure before the experiment. The question in Figure 1 was shown on the screen by the eye tracker system. The participants read the material and clicked on the spot of his/her answer on the computer. There were no time limits.

3. Data Collection, Data Analysis and Results

During the visual test, the eye tracker used 180Hz sampling rate to record every participants' eye movement data. If the fixation duration of the sample was shorter than 80 milliseconds, they were excluded to filter out the great amount of fast saccades. The remaining qualified samples were used for analyzing eye movement data. ROI Splitter was used to define the ROIs of the digital circuit in the test (Figure 2). According to the calculation results of both the Fixation Calculator software and the Saccade Statistics software, the number of saccades for each participant was 58x58=3364 times. Based on the ROI definitions in Table 1, this number was then integrated into 9x9=81 times. Due to the large variance between the participants' saccade numbers, a combined calculation of integrative saccades was adopted. Table 2 and Table 3 show integrative saccades of the high-grade group and the low-grade group. In these two tables, the saccade starts from the column ROI to the row ROI. Since saccades within an ROI are not considered in this paper, the diagonal lines in these two tables are zero by default.

Table 2 shows integrative saccades of the high-grade group between nine ROIs of the digital circuit. The higher the percentage indicates the higher the saccade rate. In order to express in a more convenient and clear way, "(from, to) = (R_7, R_6) = 5.13%" stands for "the percentage of integrative saccades from INPUT W (R_7) to the CLOCK (R_6) is 5.13%". The integrative saccades of the high-grade group's reading behavior may be observed in Table 2: (1) saccades starting from R_7, R_6 and R_8 ROI has the top three highest percentages (16.72%, 14.59% and 13.78%); (2) the top three saccade destinations are R_7, R_6 and R_8 ROI, with 15.69%, 15.62% and 13.42%, respectively; (3) (R_9, R_8) =

5.21% has the highest percentage. These discoveries imply that the high-grade group valued the three signals INPUT W, CLOCK, and INPUT X in the timing diagram and would inspect their symbols regularly. This is similar to the electric circuit theory as they both need to inspect the INPUT W, CLOCK, and INPUT X to infer the validity of OUTPUT Y. In addition, (R_9, R_8) = 5.21% represents the high value the high-grade group students had for the relationship between OUTPUT Y and INPUT X.

Table 2: High-grade group's (N_1=32) integrative saccades (Moving from column to row).

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	Sum:
R_1	0.00%	2.35%	1.32%	0.37%	1.69%	1.61%	1.54%	0.66%	0.29%	9.82%
R_2	1.91%	0.00%	4.99%	0.15%	0.44%	0.51%	0.81%	0.22%	0.22%	9.24%
R_3	2.27%	4.91%	0.00%	0.22%	0.15%	0.51%	0.37%	0.44%	0.29%	9.16%
R_4	0.81%	0.22%	0.95%	0.00%	0.95%	0.73%	1.10%	0.73%	1.10%	6.60%
R_5	1.39%	0.73%	0.66%	0.73%	0.00%	3.67%	2.05%	1.10%	0.51%	10.85%
R_6	0.88%	0.29%	0.73%	1.10%	4.47%	0.00%	5.13%	1.54%	1.47%	15.62%
R_7	0.88%	0.59%	0.29%	1.54%	1.54%	4.84%	0.00%	4.25%	1.76%	15.69%
R_8	0.81%	0.37%	0.44%	0.88%	0.59%	1.76%	3.37%	0.00%	5.21%	13.42%
R_9	0.59%	0.07%	0.07%	0.37%	0.37%	0.95%	2.35%	4.84%	0.00%	9.60%
Sum	9.53%	9.53%	9.46%	5.35%	10.19%	14.59%	16.72%	13.78%	10.85%	100.00%

Table 3 demonstrates the integrative saccades of the low-grade group's reading behavior: (1) saccades starting from R_6, R_5 and R_1 ROI has the highest percentages, with 13.32%, 13.20% and 12.42%, respectively; (2) the top three saccade destinations are R_1, R_5 and R_7 ROI, with 14.49%, 13.84% and 13.45%, respectively; (3) (R_3, R_2) = 5.30% has the highest percentage. These discoveries imply the low-grade group valued the two signals CLOCK and RESET in the timing diagram and would inspect their symbols regularly. This implies the low-grade group had a tendency to rely on function tables or truth tables, and that they were not familiar with J-K flip-flop or XOR gate. Furthermore, (R_3, R_2) = 5.30% represents the high value low-grade group students had for the relationship between the signal names of circuits and the signals of circuits, which was an unexpected result.

Table 3: Low-grade students' (N_2=35) integrative saccades (Moving from column to row).

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	Sum:
R_1	0.00%	3.75%	2.20%	0.26%	3.10%	1.81%	1.55%	1.03%	0.78%	14.49%
R_2	3.10%	0.00%	5.30%	0.13%	1.03%	0.52%	0.65%	0.26%	1.29%	12.29%
R_3	2.59%	4.01%	0.00%	0.13%	0.13%	0.65%	0.13%	0.52%	0.52%	8.67%
R_4	0.39%	0.39%	1.03%	0.00%	1.16%	0.13%	0.52%	0.26%	0.78%	4.66%
R_5	2.72%	1.16%	0.26%	1.94%	0.00%	4.79%	1.81%	0.65%	0.52%	13.84%
R_6	0.78%	0.65%	0.13%	0.26%	4.40%	0.00%	4.27%	1.29%	0.65%	12.42%
R_7	1.03%	0.13%	0.26%	0.65%	1.68%	4.14%	0.00%	3.62%	1.94%	13.45%
R_8	0.65%	0.26%	0.13%	1.03%	0.52%	0.65%	1.81%	0.00%	4.92%	9.96%
R_9	1.16%	0.39%	0.26%	1.16%	1.16%	0.65%	1.42%	4.01%	0.00%	10.22%
Sum:	12.42%	10.74%	9.57%	5.56%	13.20%	13.32%	12.16%	11.64%	11.38%	100.00%

SPSS was used to analyze the correlation coefficients between corresponding columns based on Table 2 and Table 3. The correlation coefficients of the integrative saccades in all the ROIs are higher than 0.8867, except R_4 (Table 4). This suggests that the difference between the high and low-grade group's integrative saccades is generally small, except R_4 which has the lowest correlation coefficients of integrative saccades than any other ROIs (0.3345). Thus, H_1 is supported. On closer examination of the R_4 column in Table 2 and Table 3, the high and low-grade groups have a larger difference in integrative saccades from signal names of the timing diagram to RESET, CLOCK, INPUT W and OUTPUT Y. This may be due to the low-grade group's (1) difficulty in reading comprehension of RESET, (2) neglect of CLOCK in reading, (3) neglect of INPUT W in reading and (4) comprehension, or reasoning difficulty in OUTPUT Y.

Table 4: The correlation coefficients of integrative saccades between high and low-grade groups.

From where	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9
Correlation coefficient	0.8867	0.9187	0.9715	0.3345	0.9355	0.9319	0.9572	0.9868	0.9442

4. Conclusion and Implications

The purpose of this paper is to explore the difficulties in digital circuit reading comprehension. The integrative saccades between the reading processes of high and low-grade students in Table 2 and Table 3 support the hypothesis of differences between the reading process of high and low-grade students.

The reading saccades of the high-grade group imply that they valued INPUT W, CLOCK, and INPUT X in the timing diagram and would inspect their symbols regularly. This is similar to the electric circuit theory as they both need to inspect the INPUT W, CLOCK, and INPUT X to infer the validity of OUTPUT Y. In addition, $(R_9, R_8) = 5.21\%$ represents the high value high-grade group students had for the relationship between OUTPUT Y and INPUT X.

The reading saccades of the low-grade group imply that they valued CLOCK and RESET in the timing diagram and would inspect their symbols regularly. This implies that the low-grade group had a tendency to rely on function tables or truth tables, and that they were not familiar with J-K flip-flop or XOR gate. Moreover, $(R_3, R_2) = 5.30\%$ represents the high value low-grade group students had for the relationship between the signal names of circuits and the signals of circuits, which was an unexpected result.

Based on the findings, the low-grade group had more difficulties in reading the timing diagram of RESET and OUTPUT, and fewer difficulties in reading the timing diagrams of CLOCK and INPUT. Difficulties in reading comprehension also appeared when calculating OUTPUT. Therefore, by improving the low-grade group’s familiarity with digit elements and function tables/truth tables, reading comprehension in timing diagrams of RESET and OUTPUT, emphasizing the importance of timing diagrams of CLOCK and INPUT, and improving the ability to calculate OUTPUT may improve students’ abilities in digital circuit reading comprehension. This paper provides evidence of difficulties in digital circuit reading comprehension and contributes to the field of learning science.

However, the only type of material used in this experiment was the positive level-triggering J-K flip-flop, which limited the evidence and findings in this paper.

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