ASSESSMENT OF HUMAN PERFORMANCE IN INDUSTRY 5.0 RESEARCH VIA EYE-TRACKING AND COGNITIVE BIASES

by

Dana Isam Hamarsheh BS, MSEM, MS

A Dissertation Presented in Partial Fulfillment
of the Requirements of the Degree
Doctor of Philosophy

COLLEGE OF ENGINEERING AND SCIENCE
LOUISIANA TECH UNIVERSITY

May 2023

LOUISIANA TECH UNIVERSITY

GRADUATE SCHOOL

March 28, 2023

Date of dissertation defense

We hereby recommend that the dissertation prepared by

Dana Isam Hamarsheh

entitled **ASSESSMENT OF HUMAN PERFORMANCE IN INDUSTRY 5.0 RESEARCH VIA EYE-TRACKING AND COGNITIVE BIASES.**

be accepted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Engineering, Materials & Infrastructure Systems Conc.

Mary Fendley
Supervisor of Dissertation Research

Jay Xingran wang
Head of Engineering

Doctoral Committee Members:
Joseph Cortez
Jun-Ing Ker
Pradeep Chowriappa
Stanley Cronk

Approved:

Hisham Hegab
Dean of Engineering & Science

Approved:

Ramu Ramachandran
Dean of the Graduate School

GS Form 13a
(01/20)

ABSTRACT

Manufacturing assembly is combining previously made components or subassemblies into a final finished product. The assembly process can be manual, hybrid, or fully automated. Human operators who are involved in assembly use their judgment to perform the process. They collaborate with the other work agents such as assembly machines, robots, smart technologies, and computer interfaces. The recent Industrial revolution, Industry 5.0, exploits human expertise in collaboration with efficient and accurate machines. Manufacturing facilities that feature Industry 5.0 work settings require higher expectations, higher accuracy, sustainability solutions, mass customization of products, more human involvement, and digital technologies in smart workstations. Given these features, the cognitive load exerted on human workers in this environment is continuously increasing, leading to the use of cognitive heuristics. Cognitive biases are getting more attention in the cognitive ergonomics field, to help understand the operational behavior of workers. Manufacturing facilities can integrate cognitive assistance systems to work in parallel with physical and sensorial assistance systems. Cognitive assistance systems help toward better work conditions for workers and better overall system performance. This research explores the impact of human thinking style and using a cognitive assistance system on workers' cognitive load, bias-related human performance, and user satisfaction. This research presents the design and experimental implementation of a research framework based on a well-established three-layer model for implementing Industry 5.0 in manufacturing. The research framework was designed to apply the dual-system theory and cognitive assistance in Assembly 5.0. Two experiments are presented to show the effectiveness of the proposed research framework. A cognitive assistance system was designed and compared to a benchmark system from LEGO ® Company. Subjective and objective measures were used to assess the thinking style, cognitive load, bias-related human performance, and user satisfaction in Assembly 5.0. As Industry 5.0 requires higher expectations, higher accuracy, smart workstations, and higher complexity, cognitive assistance systems can reduce the cognitive load and maintain the work efficiency and user satisfaction. Therefore, this work is important to industry to expand the use of cognitive ergonomic tools and employ them for A5.0 workers' benefits.

APPROVAL FOR SCHOLARLY DISSEMINATION

The author grants to the Prescott Memorial Library of Louisiana Tech University the right to reproduce, by appropriate methods, upon request, any or all portions of this Dissertation. It is understood that "proper request" consists of the agreement, on the part of the requesting party, that said reproduction is for his personal use and that subsequent reproduction will not occur without written approval of the author of this Dissertation. Further, any portions of the Dissertation used in books, papers, and other works must be appropriately referenced to this Dissertation.

Finally, the author of this Dissertation reserves the right to publish freely, in the literature, at any time, any or all portions of this Dissertation.

Author ______________________________

Date ______________________________

GS Form 14
(8/10)

DEDICATION

This work is dedicated to my loving parents, brothers and my loving sister who always loves me and supports me endlessly. This is also dedicated to my little kids “Tia”, “Natalie”, “Yahya”, and “Yousuf” who are the pieces that make my heart full, the energy that keeps me rolling, and the colors that give my life beauty. Finally, to my soulmate “Hamzeh”. I am forever thankful for his belief in me, support to me, and everything he surrounded me with, that words cannot content.

TABLE OF CONTENTS

ABSTRACT iii

APPROVAL FOR SCHOLARLY DISSEMINATION v

DEDICATION vi

LIST OF FIGURES xi

LIST OF TABLES xv

ACKNOWLEDGMENTS xvii

CHAPTER 1 DISSERTATION RESEARCH FRAMEWORK 1

1.1 Step 1: Understand the Process through a Pilot Study (Experiment 1) 2

1.1.1 Learn the Assembly Process through Eye-tracking and Experiments 3

1.1.2 Specify the Process Variables 3

1.1.3 Choose I5.0 Work Conditions 3

1.1.4 Introduce the Cognitive Assistance System (CAS) with Technical Features . 3

1.2 Step 2: Development of the CAS 3

1.3 Step 3: Evaluation and validation of the I5.0 CAS (Experiment 2) 4

CHAPTER 2 BACKGROUND 5

2.1 The Industrial Revolutions 5

2.2 Cognitive Ergonomics 7

2.2.1 The Dual-System Theory 8

2.2.2 Heuristics and Cognitive Biases in manufacturing 8

2.3 Cognitive Assistance Systems in Manufacturing 10

2.4 Physiological Measures of Cognitive Load 11

2.4.1 Eye-tracking Areas of Application 11

2.4.2 Eye-tracking in Engineering and Manufacturing 11

2.4.3 Eye-tracking in Additive Manufacturing 13

CHAPTER 3 POINT OF DEPARTURE 15

CHAPTER 4 EXPERIMENT 1 METHODS 16

4.1 Participants 16

4.2 Apparatus and Stimuli 16

4.3 Procedure and Task Design 18

4.4 Pre-experiment 18

4.5 Assembly Phase 19

4.6 Inspection Phase 20

CHAPTER 5 EXPERIMENT 1 RESULTS AND DISCUSSIONS 21

5.1 Data Extraction 21

5.2 Annotating Areas of Interest 22

5.3 Variable Selection 24

5.4 Assembly Phase 25

5.4.1 Cognitive Load 25

5.4.2 Human Performance 30

5.5 Inspection Phase 35

5.5.1 Cognitive Load 35

5.5.2 Human Performance 36

5.5.3 Cognitive Biases Existence in Assembly 42

CHAPTER 6 EXPERIMENT 2 METHODS 43

6.1 Choosing Workplace Elements 43

6.2 The Traditional Assistance System (TAS) 45

6.3 The Cognitive Assistance System (CAS) 47

6.4 Experiment Design and Variables 49

6.5 Participants and Task Design 50

6.6 Apparatus and Stimuli 51

6.7 Pre-experiment 52

6.8 The CRT Test 53

6.9 Assistant Systems and Assembly Tasks 53

6.9.1 Task 1: Manual Assembly Task 54

6.9.2 Task 2: The Robot Automation Task 55

6.9.3 Task 1 Inspection 55

6.9.4 Task 2 Inspection 55

6.9.5 Task 3: The Hybrid Assembly Task 56

6.9.6 Task 3 Inspection: The Hybrid Assembly Products Inspection 57

6.9.7 Task 4: The 3D Printing Task 57

6.9.8 Task 4 Inspection: Inspection of the 3D-printed Part 58

6.10 NASA-TLX TEST 58

6.11 The IBM Post Study System Usability Questionnaire (PSSUQ) 60

CHAPTER 7 EXPERIMENT 2 RESULTS 61

7.1 Data Extraction 62

7.2 Thinking Style 62

7.3 Cognitive Load 63

7.4 Cognitive Bias (Human Performance) 67

7.5 User Satisfaction 70

CHAPTER 8 EXPERIMENT 2 DISCUSSION 76

CHAPTER 9 CONCLUSIONS 82

CHAPTER 10 RESEARCH GAP AND CONTIRBUTION 87

APPENDIX A PRE-EXPERIMENT QUESTIONNAIRE (EXPERIMENT 1) 89

APPENDIX B EXPRIMENT 1 ASSEMBLY INSTRUCTIONS 90

APPENDIX C QUALITY CONTROL AND MEASUREMENT SHEET (EXPERIMENT 1) 91

APPENDIX D TRANSITION MATRICES 92

APPENDIX E PRE-EXPERIMENT QUESTIONNAIRE (EXPERIMENT 2) 93

APPENDIX F POWER ANALYSIS (EXPERIMENT 2) 94

APPENDIX G THE CRT TEST (EXPERIMENT 2) 101

APPENDIX H THE TRADITIONAL ASSISTANCE SYSTEM (TAS) 103

APPENDIX I THE COGNITIVE ASSISTANCE SYSTEM (CAS) 110

APPENDIX J CAS INTERFACE TIMER CODE 118

APPENDIX K EXPERIMENT 2 INSPECTION AND MEASUREMENT SHEET 120

APPENDIX L NASA-TLX TEST 121

APPENDIX M POST STUDY SYSTEM USABILITY QUESTIONNAIRE 122

APPENDIX N EXPERMENT 2 TRAINING 129

APPENDIX O THE ROBOT AUTOMATION CODE 131

BIBLIOGRAPHY 133

LIST OF FIGURES

Figure 1-1: Three-layer model for implementing Industry 5.0. (Based on the work "Industrial Assistance Systems to Enhance Human–Machine Interaction and Operator's Capabilities in Assembly") [1]. 2

Figure 1-2: Dissertation three-step framework. 4

Figure 4-1: (Left) Experimental apparatus. (Right) (a) Pupil Capture desktop app real-time display of the experiment captured by the eye tracker cameras (b) Pupil Core eye tracker. 17

Figure 4-2: Experiment 1 procedure overview (pre-experiment, assembly phase, and inspection phase). 18

Figure 4-3: (Left) Single workstation configuration with seated worker. (Right) The workbench layout with (a) toolbox (b) measurements and inspection sheet (c) calibration target (d) eye-tracking glasses (e) assembly instructions sheet. 19

Figure 5-1: An example of dynamic AOIs in the iMotions recording with assembler gaze in the middle of the AOI. 23

Figure 5-2: Comparison between Actual and Predicted Comprehensive Rating for selected pipe ID's. 27

Figure 5-3: The variation percent between fixation durations of attaching assembly parts and measurements of assembly parts. 28

Figure 5-4: Normalized fixation count (attaching parts AOIs). 29

Figure 5-5: Normalized fixation count (measurements AOIs). 29

Figure 5-6: Heat maps for the assembly process for two different subjects performing the same task for the same duration. More gaze points on the assembly parts (left). More gaze points on the instructions (right). 30

Figure 5-7: Standard theoretical transition path in assembly task. 32

Figure 5-8: Actual transitions between AOI's provided by gaze data. 32

Figure 5-9: Assembly phase error count for both error types (final product errors and during-assembly errors). 34

Figure 5-10: Fixation duration for inspection phase (inspected AOIs). 36

Figure 5-11: Normalized fixation count for inspection phase (inspected AOIs)............ 36

Figure 5-12: Standard inspection path hypothesized for the assembly inspection task in Experiment 1... 37

Figure 5-13: Actual inspection path the participants followed during the inspection of the toy car assembly... 38

Figure 5-14: Experiment 1 inspection errors contribution percent categorized by inspection error source (inspection phase).. 40

Figure 5-15: Duration of referring to assembly sheet versus number of inspection errors. 41

Figure 6-1: Industry 5.0 elements applied in Experiment 2 work environment. 44

Figure 6-2: Manual assembly, hybrid assembly, fully automated assembly, and our research elements in the Industry 5.0 work environment (based on "Changeable and Reconfigurable Assembly Systems by B. Lotter and H.-P. Wiendahl (2009)") [61]. 45

Figure 6-3: Traditional coding interface in Mindstorms® software (left). Traditional system step example (right). 47

Figure 6-4: The cognitive assistance system interface elements. 48

Figure 6-5: Experiment 2 tasks and tasks inspections sequence. 51

Figure 6-6: Experiment 2 workstations: the assembly workstation, the PC workstation, the 3D printing workstation, and the robot workstation. 52

Figure 6-7: Manual assembly of the robot's claw. (a) Assembler directing the motor in the specified degrees. (b) Enlarged view of the arm's motor in the zero direction. (c) Real-time positioning data which the assembler monitors simultaneously in Mindstorms® software. 55

Figure 6-8: Task 2 automation outcomes. 56

Figure 6-9: LEGO double-angled beam (black). The experiment substitution 3D-printed double-angled beam (red)... 58

Figure 7-1: CRT scores for subjects with the TAS... 62

Figure 7-2: CRT scores for subjects with the CAS. 63

Figure 7-3: Fixation duration for the TAS versus CAS for each AOI............................ 63

Figure 7-4: Fixation duration on the CAS and TAS interfaces. 64

Figure 7-5: Normalized fixation count for the CAS and the TAS. 64

Figure 7-6: Normalized fixation duration on the system interface for the CAS and the TAS. 65

Figure 7-7: NASA-TLX scores reported by TAS users. 65

Figure 7-8: NASA-TLX scores reported by CAS users. 66

Figure 7-9: NASA-TLX score subcategories scored for the TAS. 66

Figure 7-10: NASA-TLX score subcategories scored for the CAS. 67

Figure 7-11: Avoidance of information bias-related errors in assembly tasks for the CAS and the TAS 68

Figure 7-12: Avoidance of information bias error contribution percent for the CAS and the TAS. 69

Figure 7-13: Overconfidence bias-related errors in assembly tasks for the CAS and the TAS. 69

Figure 7-14: Overconfidence bias-related error contribution percent for the CAS and the TAS. 70

Figure 7-15: User satisfaction measured by PSSUQ scores for the Subcategory OVERALL. (a) TAS (b) CAS. 71

Figure 7-16: Figure 4 30. User satisfaction measured by PSSUQ scores. For the SYSUSE subcategory. (a) TAS (b) CAS. 71

Figure 7-17: User satisfaction measured by PSSUQ scores. For the Subcategory INFOQUAL. (a) TAS (b) CAS. 72

Figure 7-18: User satisfaction measured by PSSUQ scores. For the Subcategory INTERQUAL. (a) TAS (b) CAS. 72

Figure A-1: Pre-experiment questionnaire (Experiment 1). 89

Figure B-2: Experiment 1 assembly instructions. 90

Figure C-3: Quality control and measurement sheet (Experiment 1). 91

Figure D-4: Experiment 1 transition matrix for the assembly phase (generated by iMotions). 92

Figure D-5: Experiment 1 transition matrix for the inspection phase (generated by iMotions). 92

Figure E-6: Experiment 1 transition matrix for the inspection phase (generated by iMotions). 93

Figure F-7: Power analysis β=0.75 based on hardest task duration (left) and fixation duration (right). 94

Figure F-8: Power analysis β=0.8 based on hardest task duration (left) and fixation duration (right). 95

Figure F-9: Power analysis β=0.9 based on hardest task duration (left) and fixation duration (right). 96

Figure F-10: Normality test for the CRT. 96

Figure F-11: Normality test for the fixation Duration. 97

Figure F-12: Normality test for the fixation Count. 97

Figure F-13: Normality test for the fixation Count. 98

Figure F-14: Normality test for the PSSUQ. 99

Figure F-15: Normality test for the NASA-TLX. 99

Figure F-16: Normality test for the bias-related error count. 100

Figure K-17: Experiment 2 inspection and measurement sheet. 120

Figure L-18: NASA-TLX test (paper version). 121

LIST OF TABLES

Table 2-1: Major improvements and differences of Industry 5.0 from Industry 4.0. (Industry 5.0: A survey on enabling technologies and potential applications [7]). 7

Table 4-1: Assembled product inspection criteria. 20

Table 5-1: Common eye-tracking measures to predict human behavior [72]................. 21

Table 5-2: Experiment 1 phases and the corresponding areas of interest (AOIs)........... 24

Table 5-3: Experiment 1 variables, measures and the corresponding definitions. 25

Table 5-4: Assembly phase process errors, time of occurrence in the task, and the corresponding description. 33

Table 5-5: Inspection error types. 39

Table 5-6: Descriptive statistics summary for Experiment 1 parameters. 41

Table 5-7: Cognitive biases in Experiment 1, the stage of work where they occur and the resulting inspection errors. 42

Table 6-1: Comparison between the traditional assistance system and the cognitive assistance.. 49

Table 6-2: Experiment 2 variables and their corresponding measures. 50

Table 7-1: Experiment 2 research questions and their corresponding hypotheses (CL: 95%, α: 0.05)... 61

Table 7-2: Experiment 2 cognitive biases, stage in work of which they occur, and the bias-related assembly tasks. 68

Table 7-3: Summary descriptive statistics of the traditional assistance system (TAS) and the cognitive assistance system (CAS). 73

Table 7-4: Correlations between thinking style and CL measures. 74

Table 7-5: Correlations and t-test results. Paired parameters and the corresponding Pearson's correlation coefficient (ρ), P-value, and hypothesis test results for the mean μ. 75

Table 8-1: Subjects' in TAS and CAS groups comments in the PSSUQ comment sections.. 80

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my research advisor Dr. Mary Fendley, Associate Professor, Industrial Engineering, MALT center, College of Engineering and Science, Louisiana Tech University, for her support, encouragement of my research, and continuous excitement towards the project. In addition, I wish to thank her for her patience and kindness that made a significant difference to me and allowed me to work confidently. This dissertation would not have been possible, without her guidance and help. I also would like to thank my colleagues Lindsay Goudy, Jack Marzullo, Ali Farahani, Lauren Fogg and Ana Moscoso who were a source of positivity and support during my doctoral journey. I would like to extend my thanks to my committee members Dr. Jozeph Cortez, Dr. Jun-Ing Ker, Dr. Pradeep Chowriappa, and Dr. Stan Cronk for kindly accepting my invitation to be on my committee and for their valuable feedback.

CHAPTER 1

DISSERTATION RESEARCH FRAMEWORK

The basis of this study uses existing Human Factors methods for supporting workers in I5.0. One of the main contributions of this work is the integration of these methods to evaluate and effectively design a comprehensive cognitive assistance system (CAS) for a human in an Assembly 5.0 (A5.0) operational setting. Research work of Mark et al. introduced a three-step model that illustrates the approach to implementing I4.0 concepts in small and medium-sized enterprises (SMEs) [1]. Figure 1-1 shows how this research work fits into the model of Industry 5.0. The first layer (top layer) of the model is where the problem is identified, functional requirements of I5.0 are defined, and design solutions are proposed. At this level, enabling smart technologies such as eye-tracking are applied. The second layer of the model is where pilot projects are used to enter the implementation level. In the implementation level, pilot projects help in keeping iterations running to define the functional requirements and elements of applying I5.0 in the work environment. At this level, start-up needs are identified such as potential areas, plans, and feedback. The third layer (the bottom) is where the results of the pilot projects are used for implementation of the I5.0 at an operational level and the work transfers from project status to process status.

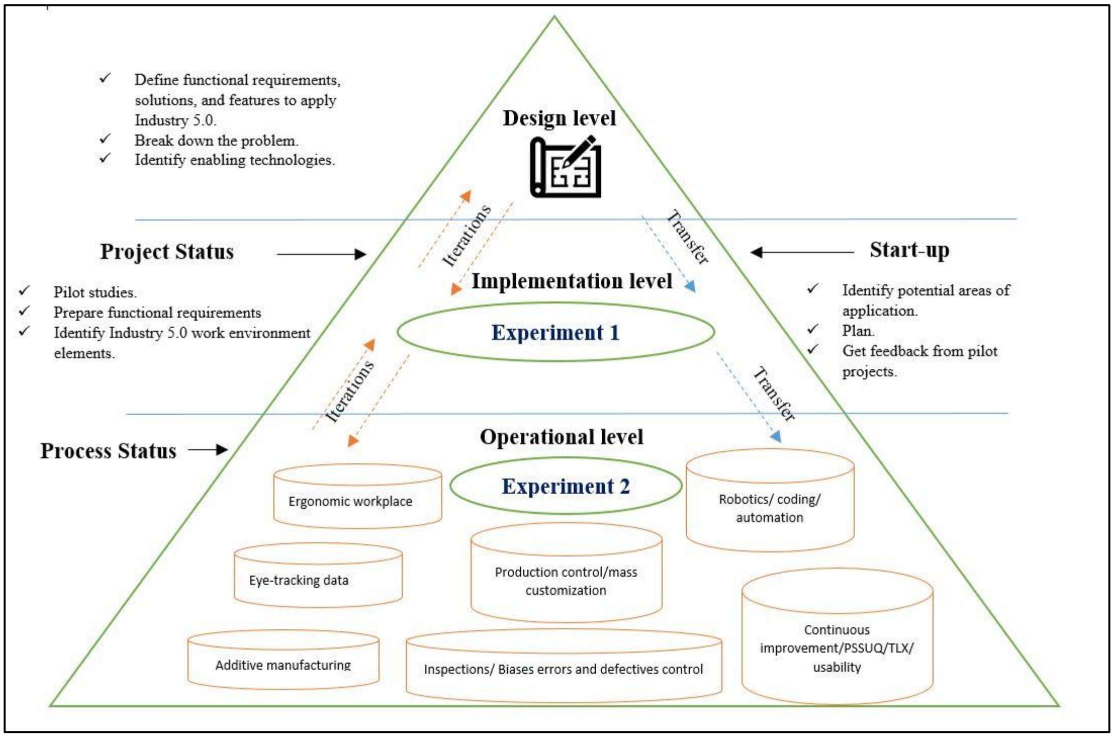


Figure 1-1: Three-layer model for implementing Industry 5.0. (Based on the work "Industrial Assistance Systems to Enhance Human–Machine Interaction and Operator's Capabilities in Assembly") [1].

1.1 Step 1: Understand the Process through a Pilot Study (Experiment 1)

The research framework (Figure 1-2) for this study was designed based on the three-layer model. Experiment 1 (the pilot study) represents the first step of the research framework. This experiment is designed as an exploratory method to understand manufacturing assembly from a cognitive ergonomics point of view. The general nature of the study is flexible and basic so that the outcome can focus on answering questions about the process and investigate the possibility of applying cognitive ergonomics concepts, tools, and technologies in a dynamic process. During the study, Subjects worked with a toy car assembly to illustrate general assembly tasks and processes.

1.1.1 Learn the Assembly Process through Eye-tracking and Experiments

The assembly is to put together pre-manufactured components permanently to form subassemblies and/or final products. The first goal of Experiment 1 is to test the capabilities of using eye-tracking technology in dynamic and complex assembly tasks.

1.1.2 Specify the Process Variables

The second goal of Experiment 1 was to determine the key relations between the manufacturing assembly work variables. The purpose of the study in this context was to gather data on the variables from the experiment and literature that influence workers conducting assembly tasks. These variables are CL, human performance, and cognitive biases.

1.1.3 Choose I5.0 Work Conditions

During the first experiment, information about I5.0 work standards, requirements, and concepts was collected through an extensive literature review. The third goal was to choose the work environment elements from I5.0 concepts to apply in the subsequent study.

1.1.4 Introduce the Cognitive Assistance System (CAS) with Technical Features

The fourth goal of Experiment 1 was to collect sufficient information about the cognitive assistance that workers need. This information includes the assistance system's technical features, physical needs, software requirements, and interface elements.

1.2 Step 2: Development of the CAS

The second step of the research framework was the development of the A5.0 CAS. In this step, the system was developed according to the outcomes of the first experiment. The interface of the system that the workers will use in their A5.0 work was designed and completed according to the outcomes revealed from the first experiment. The modality of information delivery was chosen and applied. At the end of this step, CAS was introduced.

1.3 Step 3: Evaluation and validation of the I5.0 CAS (Experiment 2)

In the third and final step, the CAS was used directly in a lab work environment to be evaluated in terms of CL, human performance, and cognitive biases.

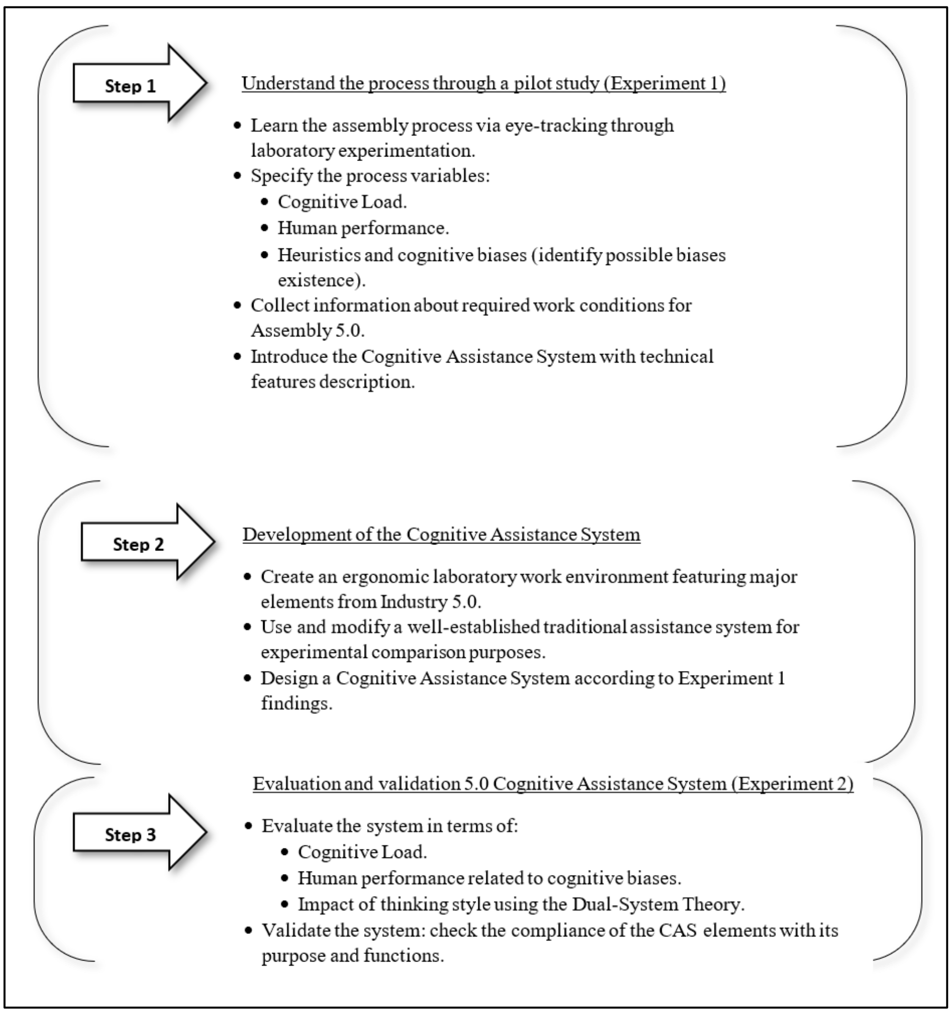


Figure 1-2: Dissertation three-step framework.

CHAPTER 2

BACKGROUND

This section provides information from previous knowledge on the topics of the Industrial Revolutions, Cognitive ergonomics, Cognitive Assistance Systems in Manufacturing, and the physiological measures of Cognitive Load. Each topic provides useful information to support the research contributions outlined in Chapter 10.

2.1 The Industrial Revolutions

Research findings defined the major concepts of Industry 4.0 and generalized them; one of these concepts is that people need to be considered the center of focus in Assembly 4.0 [2]. Out of this concept, the term operator 4.0 has been introduced. Mass customization of products create challenges for assembly operations to confront the exchange between automated systems that are highly productive and manual systems that are more flexible [1]. Industry 4.0 offers the possibility of achieving high productivity and high customization simultaneously [2]. Mass customization adds more complexity to industrial operations that needs to be studied at different levels. Currently, the Industry 4.0 concept is used to define the connection between the elements of the current manufacturing features and the new digital technologies [3]. As categorized in M. Rüßmann et al. [4]. These Key Enabling Technologies (KETs) are simulation, automated robots, horizontal and vertical systems integration, Internet of Things (IoT), cybersecurity, additive manufacturing, the Cloud, big data and analytics, and augmented reality. Research interests in Industry 4.0 focus on opportunities that can benefit industry by adopting new digital technologies. Industry benefits from the new frameworks that are developed to test the effects of applying such technologies [5]. Also, research shows the increasing interest of applying theoretical frameworks of Industry 4.0 to existing industrial environments and the positive impact of bringing the new digital technologies that Industry 4.0 calls for in its concepts [6]. Survey-based tutorials were used to investigate the differences between Industry 4.0 and Industry 5.0 [7]. Also, research discusses applications and supporting technologies that can be used in various applications such as smart healthcare, supply chain and production, smart education, cloud manufacturing and disaster management [7].

Table 2-1 shows a comparison of Industry 4.0 and Industry 5.0 in terms of improvements and concepts. Mass customization adds more complexity to industrial operations that needs to be studied at different levels.

Table 2-1: Major improvements and differences of Industry 5.0 from Industry 4.0. (Industry 5.0: A survey on enabling technologies and potential applications [7]).

Comparison	**Industry 4.0**	**Industry 5.0**
Production type	Mass production	Mass personalization (humans will guide robots).
Customer satisfaction	Normal customer satisfaction	Enhanced customer satisfaction and meets more detailed customer needs.
Improving mass productivity approach	Using smart connections between devices and required applications through machine learning technique.	Utilizing the unique human judgement and cognitive abilities in collaboration with accurate and smart machines.
Quality of production	Traditional quality tools.	Enhanced quality tools such as assigning repetitive tasks of machines administered by clever intervention from humans at the same time.
Usage of skilled jobs	Moderate	Enhanced
Sustainability	Somewhat considered	Continuously considered
Usage of collaborative robots (Cobots)	Introduces the concept	Connect collaborative robots (Cobots) with human workers to have the best of both worlds.
Decision making	Analytics and operating intelligence	Create models to make more accurate decisions and support predictive analytics and operating intelligence

2.2 Cognitive Ergonomics

Cognitive Ergonomics is defined as the ergonomics of mental processes to improve operator performance. One of the Cognitive Ergonomics concepts is to find a balance between the human's cognitive abilities and limitations, as well as the machine, task, and environment [8]. Cognitive ergonomics subject concentrates on the quality of work outcomes versus traditional or physical ergonomics looking at the quality of working positions [9]. Traditional ergonomics aims to reduce operator fatigue and discomfort resulting from work conditions. However, the nature of human work has changed significantly from working only with the body to apply given instructions and standards to working more with the mind. The increased demand for technology, along with the use of complex procedures, has imposed more pressure on operators [10].

2.2.1 The Dual-System Theory

The Dual-system theory is a well-established theory of human thinking style from cognitive psychology. It is supported by many empirical studies [11]. Daniel Kahneman, in his book Thinking, Fast and Slow [12], introduced the dual-system theory to people outside cognitive psychology.

2.2.2 Heuristics and Cognitive Biases in manufacturing

Cognitive biases are how individuals take shortcuts to divert from good judgment. Kahneman and Tversky defined several cognitive biases that affect human behavior [13]. In manufacturing, cognitive biases possess a unique definition that differentiates it from its psychological character. For example, in the operational management field, heuristics and cognitive biases are defined as behavioral operations (the explanation of human behavior in manufacturing operations). Behavioral operations and cognitive biases in this context are directly related to the stage of the work in manufacturing. Cognitive biases in behavioral operations can be assessed in four work stages: acquisition of information, processing of information, outcome stage, and feedback information stage [14]. Studies explored cognitive biases in lean manufacturing as an effort to benefit from biases instead of considering them as a source of work inaccuracies. Such studies investigated the possibility of projecting lean manufacturing concepts on several types of cognitive biases to improve work outcomes [15]. The mitigation of cognitive biases benefits steel production processes to improve manufacturing lead time and resolve the lead time syndrome in the production planning and control (PPC) stage of the work [16]. To acquire practical research results, a study collected a large amount of data from various manufacturing firms to analyze the effect of cognitive biases on workers, employees, and R&D personnel. In particular, the effect of cognitive biases shows significant improvement in the product creativity. The study shows the effect of shared heuristics on coworkers using empirical and theoretical methods [17]. CRT scores are investigated for their relationship with the cognitive biases of conservatism, overconfidence, and other biases. Therefore, the CRT can measure the difference between the reasoning and thinking style [18].

2.2.3 Cognitive Load in Assembly

In assembly, cognitive performance is the degree to which individual workers can understand and process relevant signals from the assembly situation; and finally, make decisions that lead to actions that perform correct component assembly [3]. However, cognitive workload concerns taking in sensory signals, interpreting them, and decide based on that process, while mental workload seems to include a broader range of performance-affecting factors apart from cognition [19]. Manual assembly can be assisted by mechanized or automated systems for feeding, handling, fitting, and checking operations [20]. Understanding CL in manufacturing can lead us to design better workplaces for the personnel on the shop floor. Factors that cause high CL can be split into three levels: internal factors, external factors, and the activity space [21]. Material presentation, information presentation, and situations with and without component variations are considered factors that affect human performance in assembly [22].

Cognitive load assessment tool is developed for such a purpose [23]. Other factors that affect worker's CL are studied in a wider application using a real assembly line work environment [19]. All the studies concerning assembly cognitive aspect aims to reduce CL, understand the process from a cognitive point of view and offer solutions that suit new assembly line styles. In the efforts to measure CL in Industry 4.0, a study shows that using a behavioral video coding scheme can identify assembly behaviors affecting CL in assembly 4.0 [24].

2.3 Cognitive Assistance Systems in Manufacturing

One of the major benefits of cognitive assistance systems is the information and support that they can provide in real time during any task. They help the user with providing information processing solutions and with the implementation part of the work. Examples of cognitive assistance systems include smartphones, virtual reality, augmented reality, tablets, smartwatches, and wearables. Cognitive support assistance systems provide information and guidelines for actions, steps, and processes to generate rated feedback. In addition, cognitive assistance systems can contribute to data collection process for users such work progress data, working speed, and time consumed [1]. Physical assistance systems help to reduce physical strain and ensure that the task can be performed. Examples are lifting aids or exoskeletons. Informational assistance systems, which are, in this context, listed only as cognitive assistance systems, provide workers with the information they need to complete tasks [4] A precise definition of the term "assistance system" is problematic because of its different associations and perspectives. In a broader sense, "assistance" means the addition of external capabilities to solve a task [4].

2.4 Physiological Measures of Cognitive Load

Physiological measures are used to assess CL. These measures include cardiovascular and eye activity measures [25], Electrophysiological measures such as heart rate [26], Muscle activity and cardiovascular response during computer-mouse work with and without memory demands [27], heart rate to measure CL in program running versus problem-solving tasks [28], heart rate measures used to predict perceived CL [29] Monitoring cognitive processes through pupil and cardiac response [30], eye measures such as blink frequency and duration in simulated flight task [31].

2.4.1 Eye-tracking Areas of Application

Eye tracking technology is one of the physiological measures that is progressively being used in measuring operator CL, especially in safety-critical applications [32]. It is used to understand and assist human performance in various fields such as psychology [33], air traffic control (ATC) and aviation [25], [34], [35], human-computer interaction (HCI) [36], food industry [37], automation [38], driving safety [39], [40], However, eye tracking application in engineering and manufacturing is still narrow. Engineering field is considered an exact science, and it mostly relies on physical and functional constraints [41], so, usage of eye-tracking technology in engineering is still growing. Eye tracking applications are categorized into four major groups, including neuroscience and psychology, marketing/advertising, computer science, and industrial engineering and human factors [42].

2.4.2 Eye-tracking in Engineering and Manufacturing

The need to improve workplaces in the presence of technological advances creates new challenges and needs for new technologies to be applied [43]. Earlier, companies and industrial facilities mainly focused on keeping up with digitalization by improving productivity, profitability, and efficiency. They achieved these improvements by integrating and testing new technologies on machines and platforms. Later, it was realized that improving labor conditions and working methods on the shop floor is a must [44], [45]. Despite of the widespread of eye tracking in the domains mentioned in (2.4.1), it gained more attention in engineering and manufacturing fields. In construction, eye tracking popularity is increasing, especially in situations concern construction safety and situational awareness [46] Eye-tracking has potential benefits in the design stage of construction to increase end-user satisfaction [47]. Remote eye-trackers can measure the effects of safety knowledge on construction worker's attentional allocation during hazardous situations and scenarios that can cause injuries [48]. Eye-tracking shows promising results to understand visual behavior of engineering designers and engineering drawings [49], [50]. Eye-tracking assists the automation, safety training and feedback collection for construction individuals to enhance worker's safety [51]. Eye-tracking helps to identify and classify construction equipment and operator's mental fatigue levels [52].

Eye-tracking shows useful results in the automotive industry, where it improves the quality control process by applying the technology in a real factory environment and analyzes eye signals output [41]. In manufacturing, Eye-tracking data can measure the impact of information provision to compare between laboratory and real life work conditions. Also, it helps in understanding the effect of these work conditions on productivity and value-adding activities By collecting eye-tracking data, the impact of information provision and the comparison between laboratory and real life work conditions on productivity and value-adding activities can be measured [53]. In lean manual assembly, eye tracking video analysis is implemented as one of the ergonomic enhancement techniques for the work environment. It is used to apply lean manufacturing concepts like reducing time and non-value-adding practices and enhancing the ergonomic design of the workplace. Results show that eye-tracking can be used as a biometric system to making assembly not only more ergonomic but also less error-prone and more productive [54].

Eye-tracking can be combined with cognitive biases in manufacturing. It can provide useful information to assist apprentice and skilled workers' performance. Ease of Recall and Confirmation Trap biases are tested in a manufacturing simulated environment. The study reveals that eye-tracking is an efficient tool to understand relationships between skill acquisition and attainment of the next learning level for work efficiency [55].

2.4.3 Eye-tracking in Additive Manufacturing

Additive manufacturing process is primarily driven by intuition, logical judgments, and application of engineering principles. Eye-tacking method can be used as a behavioral measure to redesign the workflow of the additive manufacturing process [56]. Eye-tracking is integrated with other techniques, such as Hidden Marcov Modeling and mining design heuristics, to understand the designing stage for additive manufacturing. This techniques collaboration work together to draw artifacts about manufactural and quality of the final 3D-printed product [57]. Eye-tracking and questionnaires help in understanding the perception of end-user of 3D-printed products [58]. Additive manufacturing is considered a crucial element in Industry 4.0. Aspects of smart materials, process development and new technologies trends in additive manufacturing are investigated to be integrated in Industry 4.0. Smart additive manufacturing is one of the additional features of Industry 5.0 that differentiates it from Industry 4.0. While additive manufacturing in Industry 4.0 focused on customer satisfaction, it is integrated with other Industry 5.0 concepts to maximize its capabilities for energy saving and sustainability purposes [7], [59].

CHAPTER 3

POINT OF DEPARTURE

This work addresses the gap found in Industry 5.0 research that is related specifically to assembly 5.0 workers' performance and CL. To further understand assembly worker's performance, research revealed that there are two assembly mindsets [19]:

1. A product-centered mindset: This approach depends on assembler's qualifications such as work experience, personal skills, and assembly instructions perception.

2. A worker-focused mindset: This approach uses iterative methods and collaborative developments to improve the assembly process to make it smoother for worker, along with keeping the goals of reducing errors, costs, delays, and rework. Research findings encourage the focus on this mindset.

CHAPTER 4

EXPERIMENT 1 METHODS

In Experiment 1, Pupil Core eye-tracking glasses were used to acquire the eye movement data of the participants as a measure of CL. Eye-tracking data and video recordings were used to understand assembler's behavior during manual assembly tasks, to identify potential cognitive biases and to study human performance

4.1 Participants

The study comprised 13 participants, 4 females and 9 males. All participants were within the age range of 18–25 (Mean 21.5 years, SD 3.5 years). The participants were undergraduate students from the college community. Two subjects had previous manual assembly experience. The primary task in the experiment was to build a toy car using hand tools. The subjects were volunteers and were not paid for participating. Prior to taking part in the study, informed written consent was obtained from each subject. This study was conducted in compliance with the Louisiana Tech University Internal Review Board (IRB).

4.2 Apparatus and Stimuli

A Pupil Core wearable eye tracker from Pupil Labs [60] was used to record the visual measure while performing the experiment (Figure 4-1). The eye tracker features an accuracy of 0.6˚. It comprises a world camera and two eye cameras. The world camera is a 180˚ adjustable camera with a 60 Hz sampling frequency and a 1280 × 720 pixels resolution. The eye cameras are adjustable in the front/back direction and can record the user's gaze point, pupil behavior and blink with a 200 Hz sampling frequency and a 192×192 pixel resolution. The Pupil Core eye tracker is chosen because of its features suitable for assembly tasks. The eye tracker is made from lightweight (22.75g) PA12 Nylon and can be worn over safety glasses which can reduce the interference with the assembly dynamic tasks. The eye tracker was connected to a PC with Windows 10 operating system via USB. Pupil Capture v3.4.0 desktop app was used for real-time data capturing and recording.

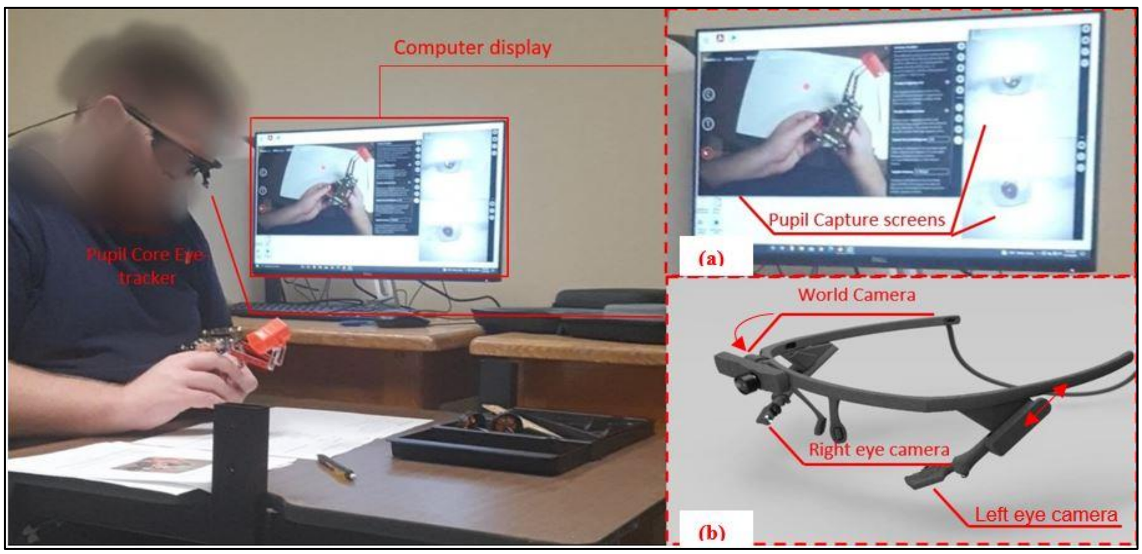


Figure 4-1: (Left) Experimental apparatus. (Right) (a) Pupil Capture desktop app real-time display of the experiment captured by the eye tracker cameras (b) Pupil Core eye tracker.

The experiment was held in a controlled-light laboratory room. This experiment was designed with a single bench workstation configuration and a seated worker's posture. The workstation was located beside the computer, with the worker away from the screen to prevent distractions. These sets were kept for all participants.

The workstation was equipped with an organized toolbox that was previously prepared for each participant with all the tools and subassemblies. The worktable had the measurements and inspection sheet, eye-tracking calibration target, eye-tracking glasses, and the assembly instructions sheet.

4.3 Procedure and Task Design

The final assembly product was a toy car. The experimental procedure is summarized in Figure 4-2.

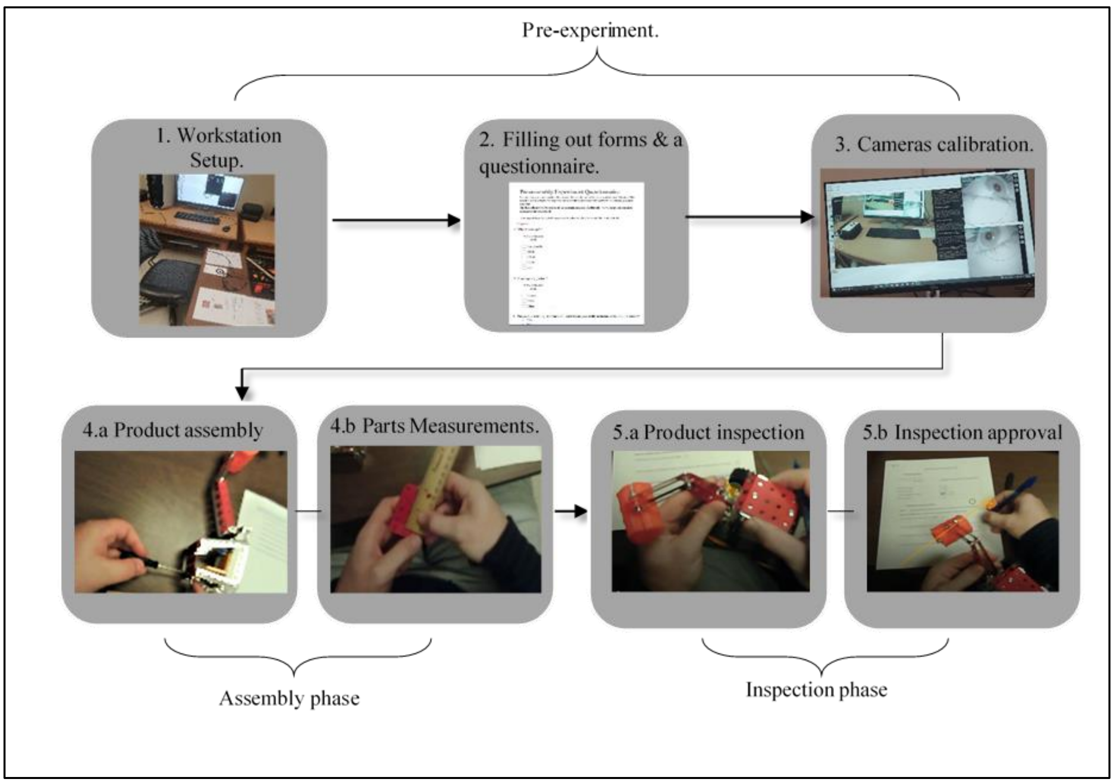


Figure 4-2: Experiment 1 procedure overview (pre-experiment, assembly phase, and inspection phase).

4.4 Pre-experiment

Before the experiment began, each participant was briefed on the task requirements, calibration procedure, and how much time was allowed. However, no previous training was provided to the participants. All participants were required to complete the task within a one-hour time limit. This time limit included filling out the consent forms, answering the questionnaire (Figure A-1), calibrating the eye-tracker, and finishing the task. Before executing the assembly task, the eye-tracker was adjusted based on each participant's face and head features. The glasses were calibrated using a 5-point on-screen calibration method for each participant.

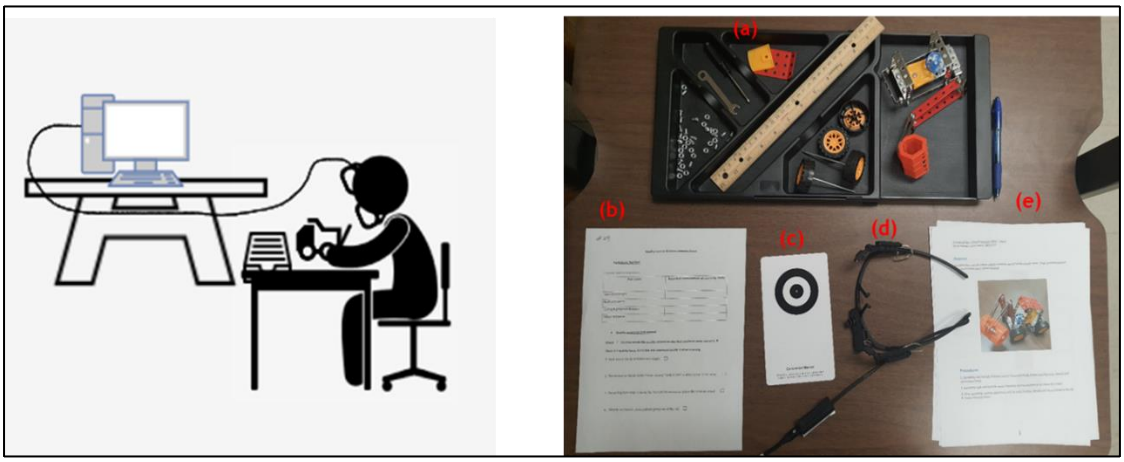


Figure 4-3: (Left) Single workstation configuration with seated worker. (Right) The workbench layout with (a) toolbox (b) measurements and inspection sheet (c) calibration target (d) eye-tracking glasses (e) assembly instructions sheet.

4.5 Assembly Phase

Assembly instructions (Figure B-2) were provided using assembly and instructions sheet with a step-by-step manner. The first page of the instructions sheet shows a final product picture participants could refer to at any point. In addition, the assembly instructions sheet described provided parts, tools, and subassemblies.

The participants were not aware of the time during the process. The process ended either by the participant informing the lab attendant or by the lab attendant announcing that the one-hour time block is up. However, no participants exceeded the time limit.

4.6 Inspection Phase

The inspection phase of the experiment is performed directly after finishing the assembly. Participants are required to inspect the finished product for four critical subassembly components as shown in Table 4-1. Inspection requirements are provided on the Measurements and inspection sheet. Participants are asked to inspect four critical parts of their assembled product and provide their judgement on the inspection sheet. The critical parts are chosen based on the importance in relation to the final product required function.

Table 4-1: Assembled product inspection criteria.

Inspected Part	**Inspection Criteria**
Seating area	Sturdiness and alignment
Loader head	Sturdiness and rotation angle flexibility
Ceiling	Sturdiness and direction
Wheels	Sturdiness and motion

CHAPTER 5

EXPERIMENT 1 RESULTS AND DISCUSSIONS

5.1 Data Extraction

During the experiment, the assembly process videos, and eye movements of the participants recorded by the eye tracker. Gaze movements and eye activities can explain the cognitive process and provide information about thoughts [70]. Different eye activity measures have been confirmed as useful predictors to CL such as fixations, saccades, and blinks. Research revealed that pupillometry is a promising predictor for real-time assessment of CL. In particular, the increase in fixation duration, pupil dilation and blink latency showed the increase in CL [71]. Definitions of common eye-tracking measures as defined by [72] are summarized in Table 5-1.

Table 5-1: Common eye-tracking measures to predict human behavior [72].

Measure	**Definition**	**Duration (ms)**
Gaze	The pauses of eye gaze in specific locations	-
Fixation	Eye movements with a series of brief stops in specific locations	200-300
Saccade	Eye movements from one location to another	30-80
Glissade	A gliding unintentional eye movement in replacing the point of fixation	10-40

Data was analyzed using iMotions v9.2 software. Data was obtained by converting real-time recordings of the task from the Pupil Capture- v3.4.0 software to an iMotions-compatible recording.

5.2 Annotating Areas of Interest

Each recording was analyzed and annotated individually. Dynamic AOIs were established for the two phases of the manual assembly task (the assembly phase and the inspection phase). Figure 5-1 shows an example of annotated dynamic AOIs in iMotions. Each geometrical shape represents the part of the work that we are interested in collecting eye data for. Each AOI dimension was adjusted continuously according to the assembly object's shape to achieve higher eye-tracking data accuracy.

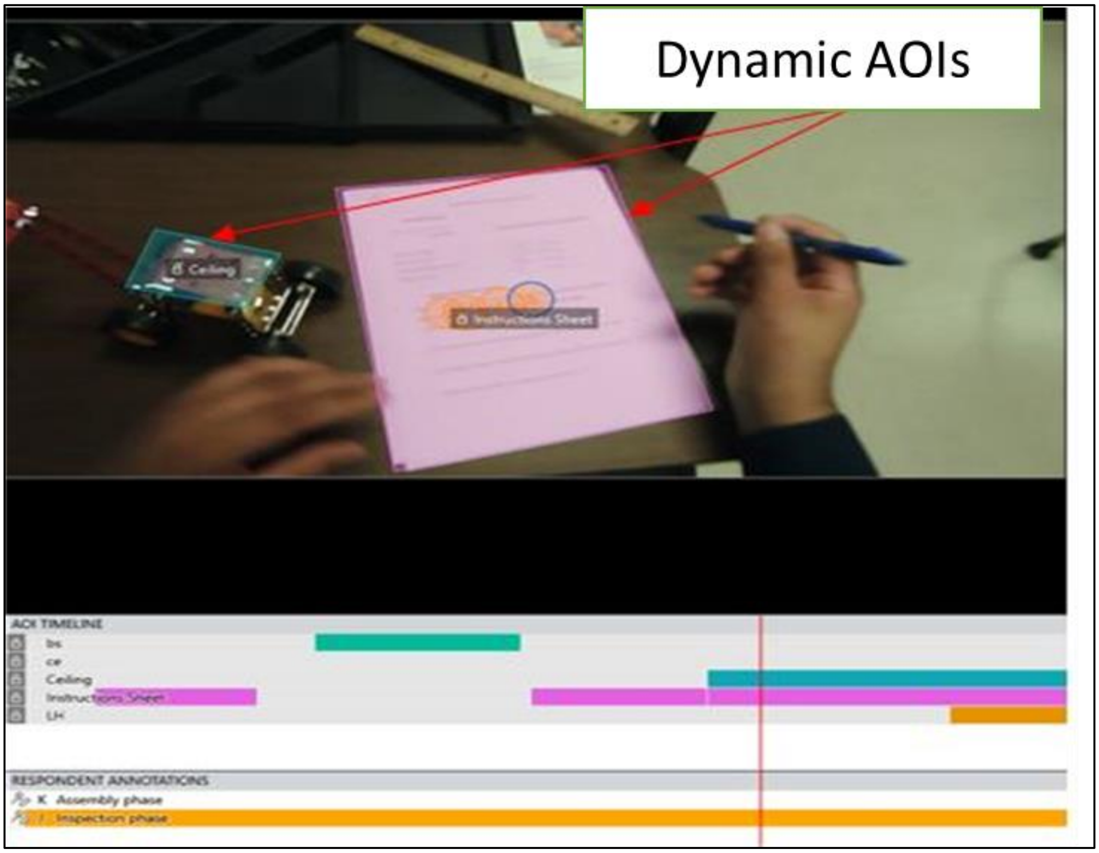


Figure 5-1: An example of dynamic AOIs in the iMotions recording with assembler gaze in the middle of the AOI.

This experiment had two dynamic AOIs that were used across both phases, four dynamic AOIs for the assembly phase, and seven dynamic AOIs for the inspection phase (Table 5-2). The two common AOIs are the assembly sheet and the final product picture. The remaining AOIs represent the parts of the product that the assembler is required to attach or inspect. The assembly phase represents the phase where the subject is attaching parts and subassemblies to each other to produce the required product. The inspection phase represents the part of the work where assemblers inspect parts or subassemblies as required, and record the results in the designated sheet.

Table 5-2: Experiment 1 phases and the corresponding areas of interest (AOIs).

Phase	**AOI annotation**	**Description**
Assembly phase and	AS	The assembly sheet
Inspection phase	PP	The product picture
	Measure BS L&W	Measure backseat length and width
Assembly phase	Attach BS	Attach the backseat
	Attach LH	Attach the loader head
	Measure CE	Measure the ceiling highlighted distance
	Attach CE	Attach the ceiling
	Measure DIA	Measure the wheel diameter
	Attach WH	Attach wheels
	Inspect BS	Inspect the backseat
Inspection phase	Inspect LH	Inspect the loader head
	Inspect CE	Inspect the ceiling
	Inspect WH	Inspect the wheels

5.3 Variable Selection

The experimental variables are categorized in two major categories, CL, and human performance. CL is measured by fixation duration and normalized fixation count. Human performance is measured by the transition count and number of errors. The experimental variables, their measures, and their definitions are shown in Table 5 3.

Table 5-3: Experiment 1 variables, measures and the corresponding definitions.

Variable	**Measure**	**Definition**
Cognitive Load	Fixation duration (ms)	The total time each participant fixated at each AOI.
	Normalized fixation count (fixation/ms)	The number of normalized fixations divided by fixation duration within each AOI.
Human Performance	Transition count	The number of transitions between one AOI and another.
	Number of errors	Number of defective parts in the final assembled product.

5.4 Assembly Phase

This section shows the results of CL and human performance for assembly phase tasks.

5.4.1 Cognitive Load

The assembly phase of the work was analyzed for CL and human performance. Cognitive biases existence is assessed in this phase of the work. Experiment 1 results were used to predict CL using the eye-tracking measures (fixation duration and fixation count). AOIs of the assembly phase are classified into two categories:

1. Attaching parts AOIs: areas of interest that focus on assembly processes where the assemblers attach/detach parts and subassemblies.

2. Measurements AOIs: areas of interest that focus on assembly processes where the assemblers take, and record required parts measurements. Figure 5 2 shows fixation durations for attaching parts in assembly phase.

Fixation duration data for the assembly phase was used to measure the CL during attaching parts and subassemblies until they become a finished product. Higher fixation duration shows an increase in CL during the corresponding assembly job. As seen in Figure 5-2, the highest CL was when assembling the ceiling subassembly of the product. However, the lowest CL was observed on the assembly sheet.

Results showed that the highest CL was exerted by participants on measuring wheel diameter for wheels subassemblies (Figure 5-3). These findings play an important role in reducing the error count that occurs when taking measurements.

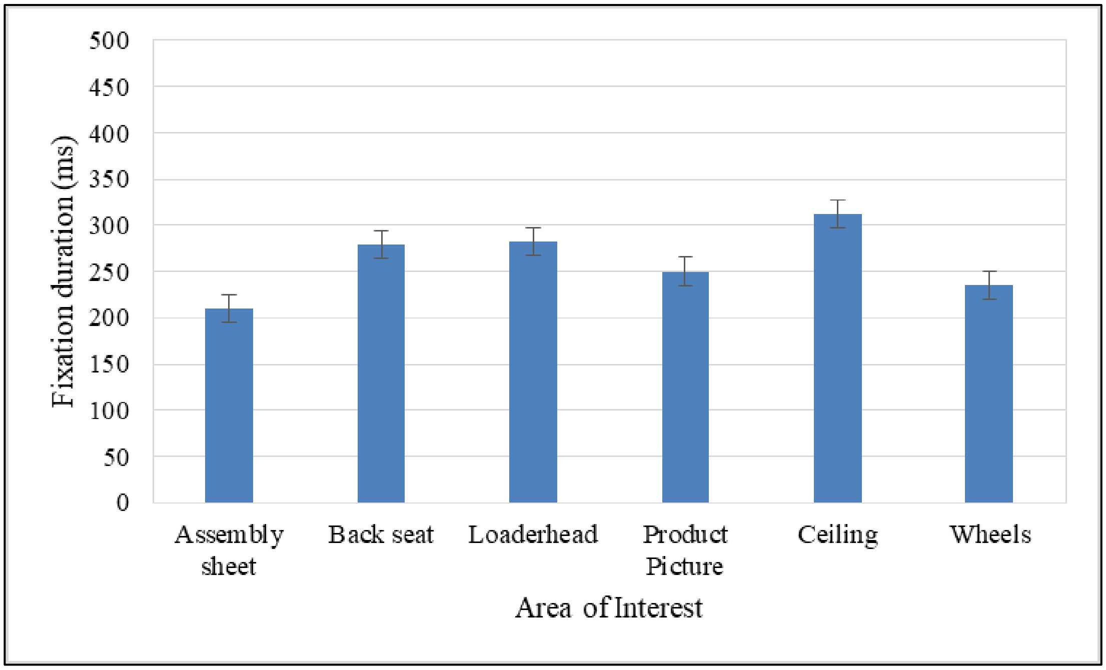


Figure 5-2: Comparison between Actual and Predicted Comprehensive Rating for selected pipe ID’s.

The within-subject variation percent in fixation duration is calculated using the following equation.

$$\frac{\text{Measurement fixation duration-Attaching part fixation duration}}{\text{Measurement fixation duration}} \times 100\ (\%)$$

Results showed that 69% of the subjects had an increase in fixation duration while performing measurement requirements versus attaching assembly parts (Figure 5-4). The highest increase was 56% in the favor of measurement tasks. These results were used as a predictor to CL related to assembly tasks that require assembly skills versus tasks that require measurement skills.

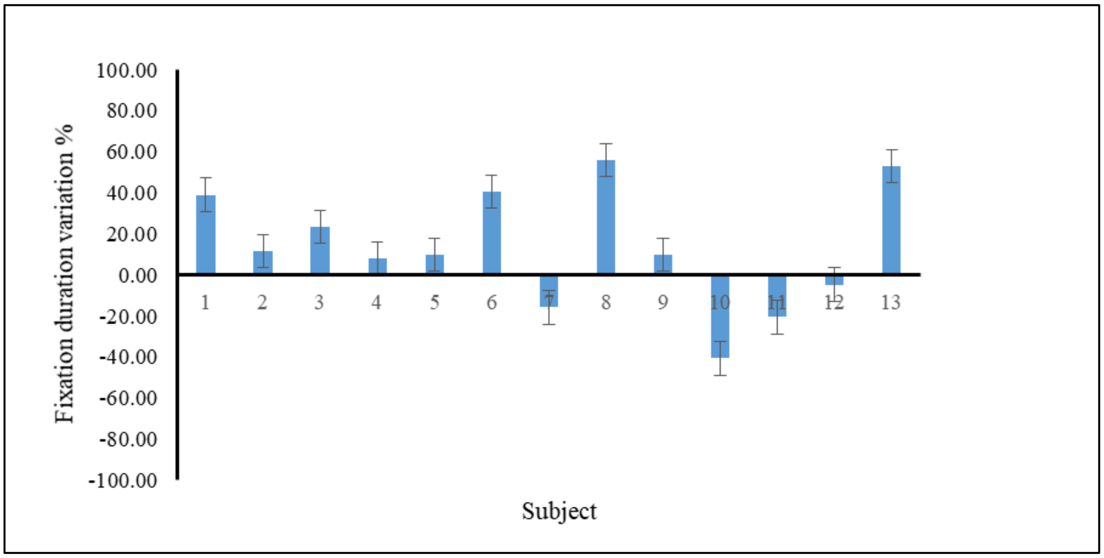


Figure 5-3: The variation percent between fixation durations of attaching assembly parts and measurements of assembly parts.

For reliable comparisons, the fixation count data was normalized. 30% of the total fixations was observed in the assembly sheet AOI. It can be stated that 30% of CL is dedicated by assemblers to read instructions (Figure 5-5). Among attaching parts, fixation count on the ceiling subassembly consumes 20% of the total CL.

Among attaching parts tasks (Backseat, Loader head, Ceiling, and Wheels), the least CL was consumed when attaching the wheels subassembly with 10% of the total fixation count (Figure 5-5). The geometry being easy to comprehend and the subjects being familiar with the use of wheels in practical applications explain these outcomes. The complexity of ceiling subassembly geometrical features increased the exerted CL on that AOI.

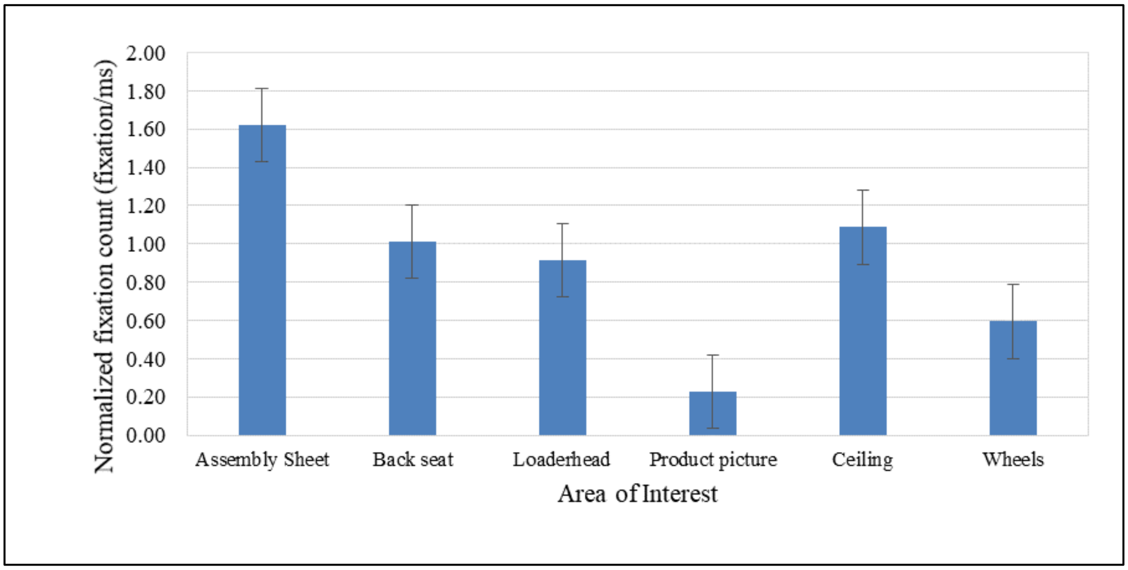


Figure 5-4: Normalized fixation count (attaching parts AOIs).

More than 50% of taking measurements CL, was documented for the back seat subassembly (Figure 5-6). This increase in CL can be explained by the irregular and complex geometry of the back seat.

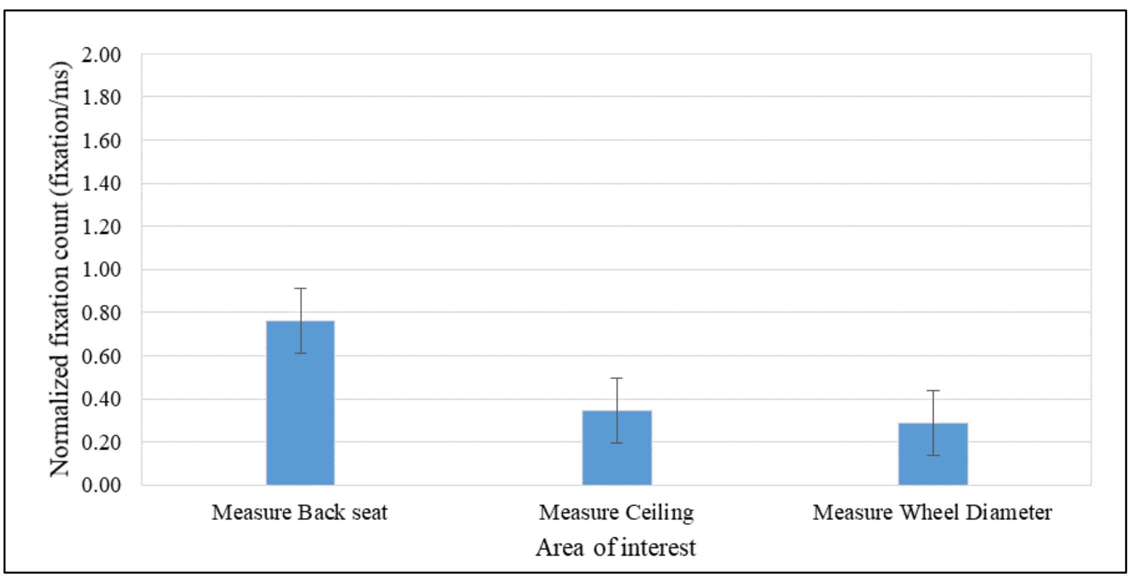


Figure 5-5: Normalized fixation count (measurements AOIs).

Heat maps are visualizations used to show the general distribution of gaze points. They are typically displayed as a color gradient overlay on the presented stimulus. The red, yellow, and green colors represent in descending order the amount of gaze points that were directed towards parts of the AOI. Heat maps in the assembly process were used to understand the assemblers' visual focus variations. Figure 5-7 shows a comparison between two assembler's visual behaviors for the same task and same mapped duration using heat maps.

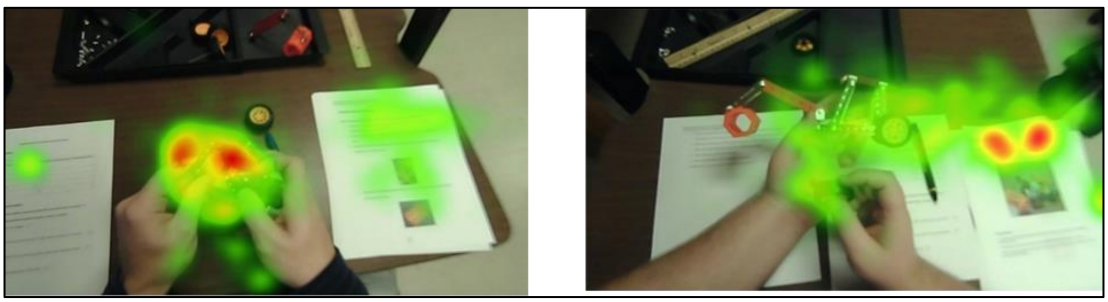


Figure 5-6: Heat maps for the assembly process for two different subjects performing the same task for the same duration. More gaze points on the assembly parts (left). More gaze points on the instructions (right).

5.4.2 Human Performance

In Experiment 1, Human performance was assessed by the transition count and the number of assembly errors. The transition count data was calculated for all participants from the eye-tracking transition matrices extracted from iMotions. However, assembly error count is retrieved from individual subject's recording.

A transition is defined as two subsequent fixations falling into different AOIs. Ideally, participants are expected to follow a standard path to execute the assembly process. Figure 5-8 shows the predicted standard path for the tasks. Eye-tracking transition matrices from iMotions are analyzed to assess human performance in

Experiment 1 (Figure D-4). The results show multiple deviations from the predicted path in the actual task transitions. Figure 5-9 shows the actual path that was followed by assemblers. The rectangles represent the assembly AOIs in the order required by assembly instructions. The arrows represent the direction from/to one AOI to another. The numbers on the arrows represent the total number (sum of transitions) of actual transitions followed by all participants for that path. For example, participants transitioned for 27 times from the "Assembly Sheet" AOI to "Measure the Ceiling" AOI. More frequent transitions are expected to show human performance in the assembly task. It also shows the random behavior of assemblers rather than the expected standard behavior assumed in ideal case scenarios. Such observations help in designing work environments and improve information delivery methods to accommodate worker requirements and task complexity. Finally, the number of transitions from/to an AOI can show the AOI importance in the work.

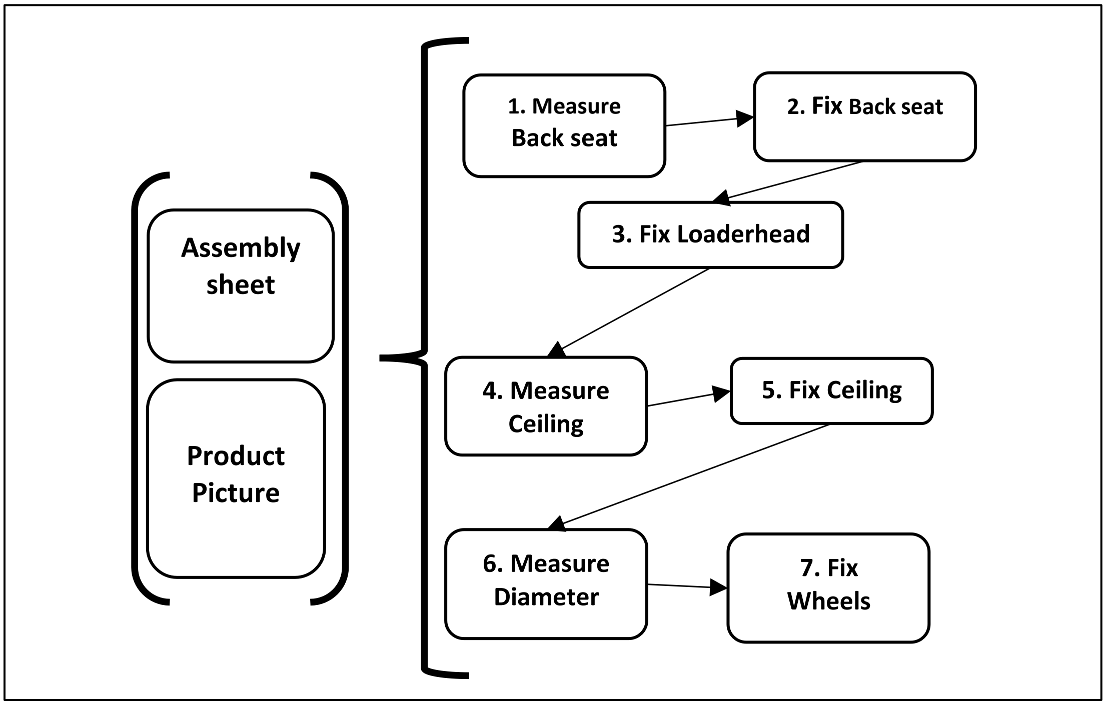


Figure 5-7: Standard theoretical transition path in assembly task.

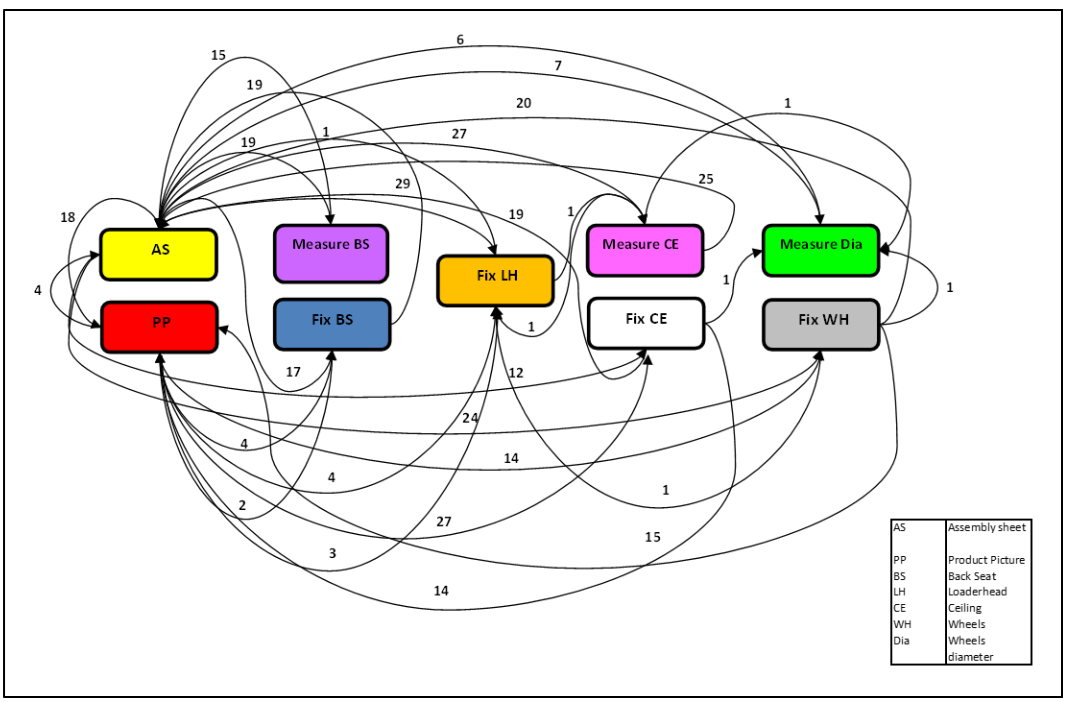


Figure 5-8: Actual transitions between AOI's provided by gaze data.

The second measure of Human Performance is the number of assembly errors. The primary goal is to detect process errors by analyzing eye-tracking provided data and observing process recordings carefully. As concluded by [73], analyzing human error in assembly (when and why they occur) can provide reliability analysis for the assembly process and measure human performance. According to [73], categorizing human error can predict the highest error occurrence probability. For example, the highest error probability is associated with assembly parts sensitive to geometry. Error categories for Experiment 1 are summarized in Table 5-4.

Table 5-4: Assembly phase process errors, time of occurrence in the task, and the corresponding description.

Label	**Description**
DURING-ASSEMBLY ERRORS (Leading to finished product errors).	
1. Interpreting requirements	Assembler misinterpreting of assembly requirements in assembly steps.
2. Steps order	Doing assembly steps in reverse when order is required and/or starting with inspection instead of assembly.
3.Direction/Alignment	Errors related to the wrong direction of a part or alignment of parts together that result in errors in the finished product.
4. Not using tools sufficiently	Not using tools when assembler must use them to perform assembly step correctly.
5. Spatial (limited access)	Errors related to points in assembly work where it's hard to access with hand and tools.
6. Shape-related error	Errors
FINISHED PRODUCT ERRORS	
1. Shape-related error	Wrong assembly of parts because of size or similarity of parts or subassemblies.
2.Direction/Alignment	Parts assembled in the wrong direction or aligned improperly with other parts/subassemblies.
3. Loose attachment/s	Final product having loose connections between parts or subassemblies.

Errors of the assembly phase were observed by analyzing individual recordings for participants (Figure 5-10). Afterwards, errors are classified into two categories based on the time they occur in the task as during-assembly errors and finished product errors. During-assembly errors represent the errors happened during assembly work, and it led to final product error. Any During-assembly error that didn't cause a final assembly error was excluded from the analysis. In contrast, final product errors represent the errors observed after the product was finished.

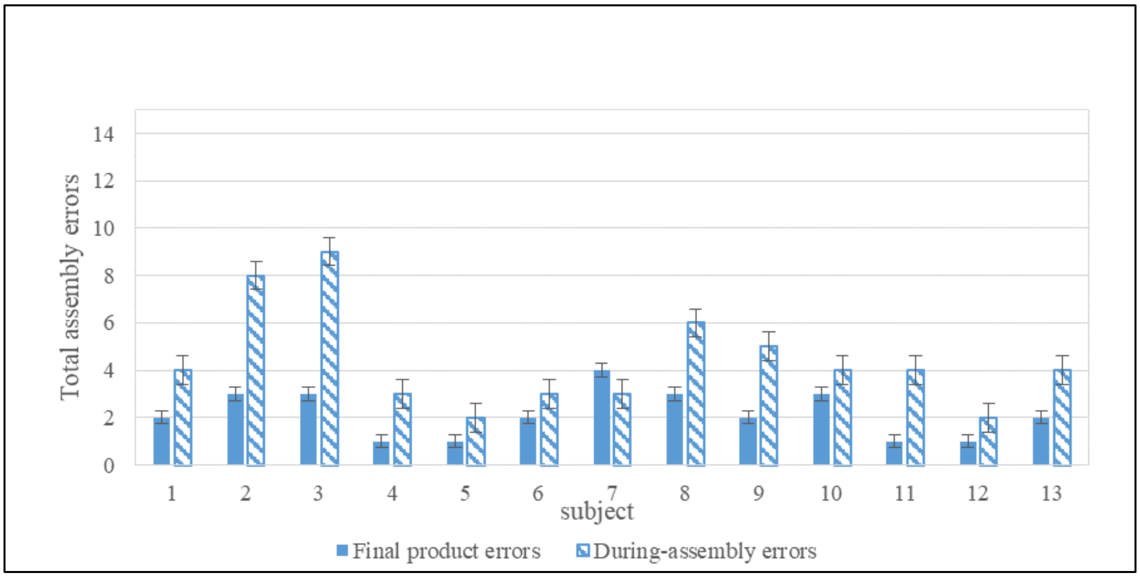


Figure 5-9: Assembly phase error count for both error types (final product errors and during-assembly errors).

The number of assembly phase errors is higher during assembly than after the assembly is finished. Loose attachments in the final assembled errors represented 24% of the overall total errors (during assembly + finished assembly errors). Loose attachments represented 85% of final product errors, where the final product had loose parts that negatively affected its expected functionality.

5.5 Inspection Phase

Assessment of CL and human performance in the inspection phase of Experiment 1 are discussed in this section.

5.5.1 Cognitive Load

The inspection phase is where the participants were required to make sure that the product looks like the final product picture, functions properly, and meets requirements described in the quality control and measurement sheet (Figure C-3). CL in inspection phase is measured by fixation duration and normalized fixation count.

Results showed that inspecting the back seat consumed the highest fixation duration (284 ms), while the ceiling consumed the least fixation duration (207 ms). The remaining fixation durations were 280 ms for the loader head, and 220 ms for the wheels. (Figure 5-11). Normalized fixation count agreed with these results (Figure 5-12). This increase in CL for inspection is because of the single point type of attachment that connects these subassemblies to the entire product structure. This type of attachment results in a higher chance of less sturdy subassembly connections, which requires more CL to inspect.

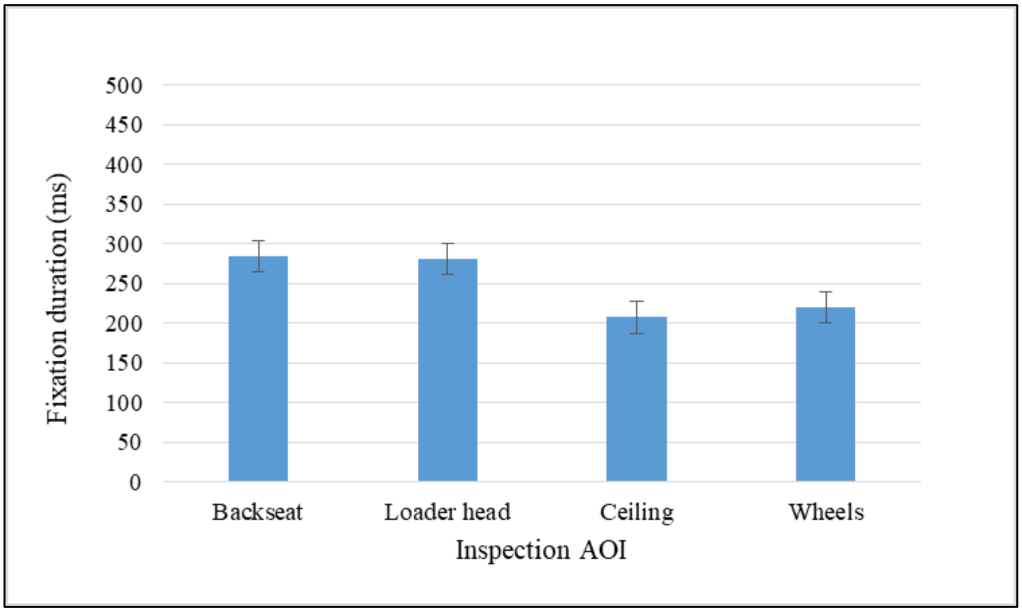


Figure 5-10: Fixation duration for inspection phase (inspected AOIs).

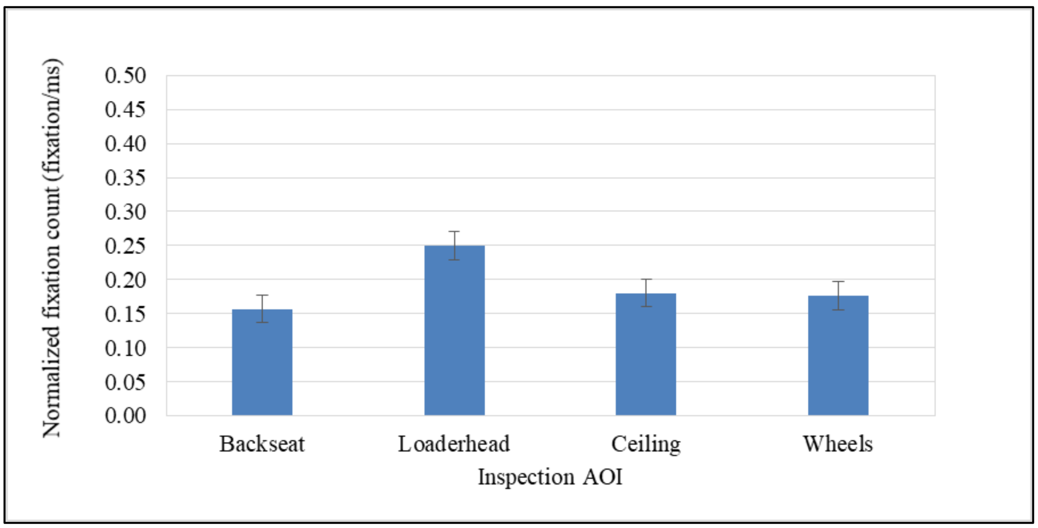


Figure 5-11: Normalized fixation count for inspection phase (inspected AOIs).

5.5.2 Human Performance

Transition count and number of errors are used to measure human performance in the inspection phase. In actual inspection procedure, subjects did not follow the standard hypothesized inspection path illustrated in (Figure 5-13). Instead, the actual inspection path is more random (Figure 5-14). The number on each arrow represents the number of transitions to/from an AOI for all subjects inspecting the corresponding AOI in the rectangles.

The highest number of transitions was observed along the standard path the standard path, which means most of the time an assembler would inspect the product as they are expected to. However, there were few transitions in the opposite directions going back to a previous AOI. That can show the importance of AOIs and the possibility of human error occurrence in that AOI. For example, there were 2 transitions after finishing the inspection process for the first inspected part (the back seat). Understanding transitions can provide feedback about the inspection behavior of an assembler and how it can be improved to superior efficiency and less CL.

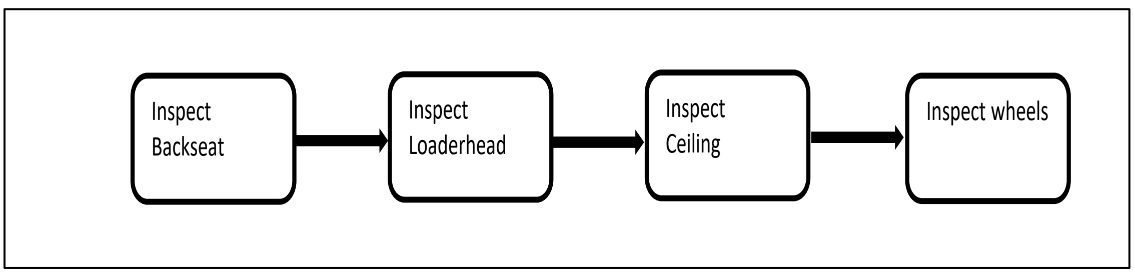


Figure 5-12: Standard inspection path hypothesized for the assembly inspection task in Experiment 1.

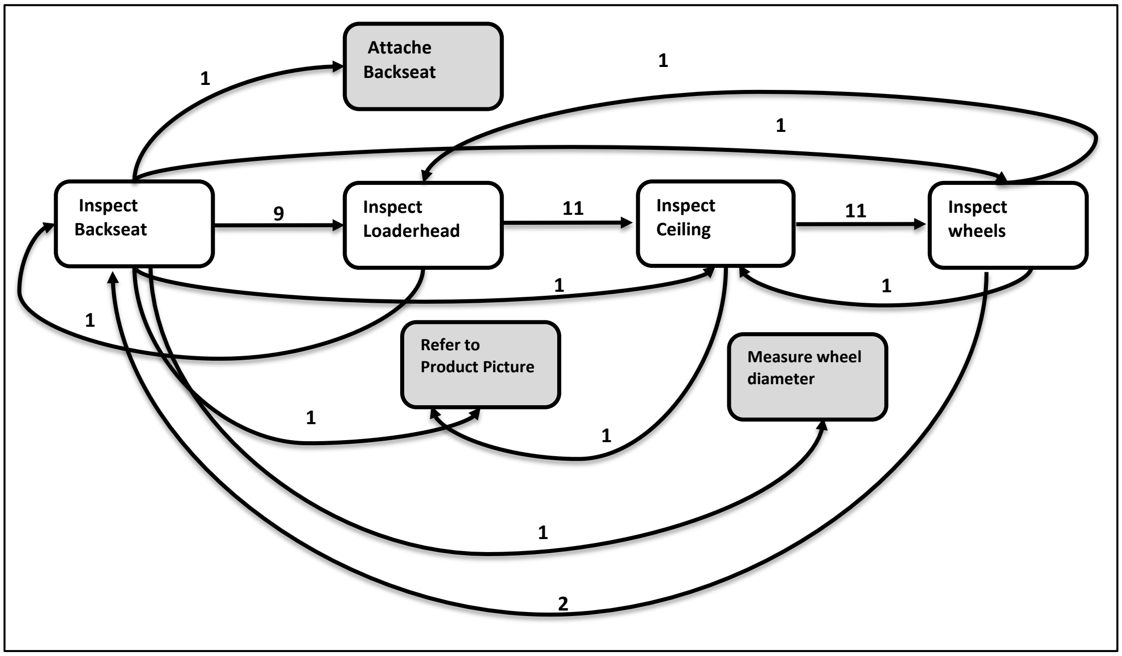


Figure 5-13: Actual inspection path the participants followed during the inspection of the toy car assembly.

Inspection error is defined as an approval of a part when it should not be approved. Table 5-5 shows the inspection error types, descriptions, and definitions.

Sources of inspection errors are illustrated in Figure 5-15. The results show that 56% of total inspection errors are due to approving loose attachments, 22% are due to using wrong inspection technique, and 9% are due to approve without inspecting and approving with wrong inspection, respectively. Finally, 4% of inspection errors were because of incomplete inspection.

Table 5-5: Inspection error types.

Label	**Description**	**Definition**
Error 1	Approve a loose attachment	When the subassembly had loose screw/nut attachment and the assembler recorded a check in the inspection sheet.
Error 2	wrong inspection technique	When the assembly was assembled in a wrong direction and the assembler approves it the inspection sheet.
Error 3	Approve a missing part	When the assembly lacks a part, and the assembler approves it on the inspection sheet.
Error 4	Approve without inspection	When the assembler recorded the inspection sheet and confirmed without inspecting.
Error 5	Approve with incomplete inspection	When the assembler inspected the subassembly partially and recorded check in the inspection sheet.

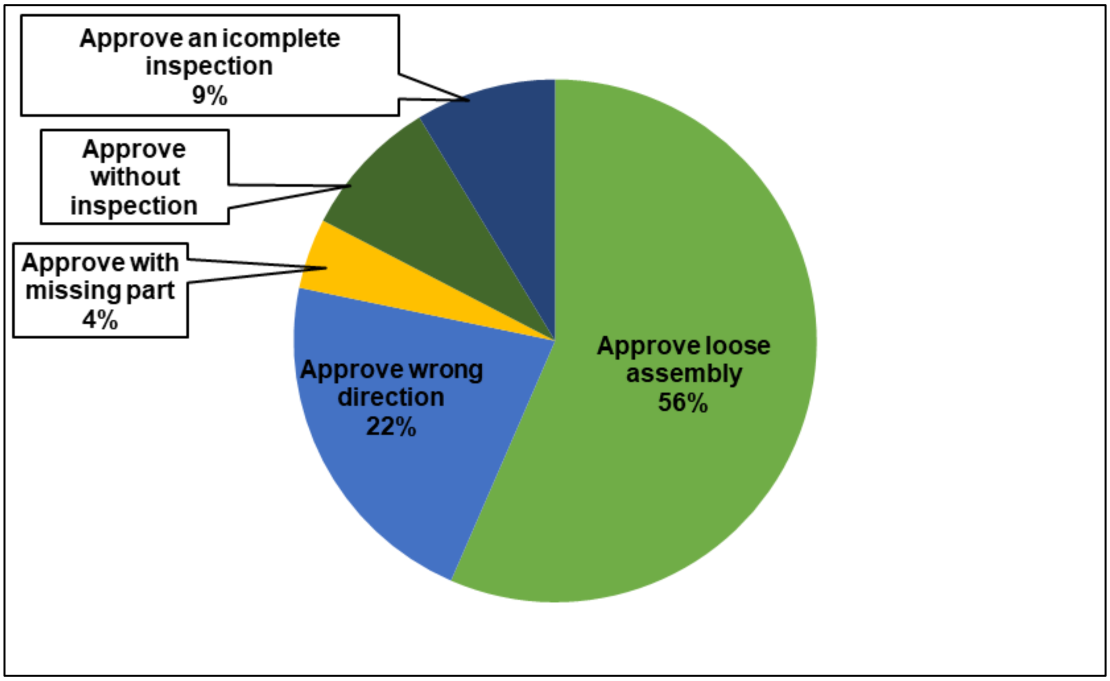


Figure 5-14: Experiment 1 inspection errors contribution percent categorized by inspection error source (inspection phase).

The relationship between clustering of inspection errors and the actual duration referred to the assembly sheet is shown in Figure 5-16. More inspection errors were observed when assemblers spent less time referring to the inspection sheet. As the inspection sheet comprised a detailed description of required inspection, longer durations helped in reducing inspection errors. Table 5-6 shows a summary of descriptive statistics for Experiment 1 parameters.

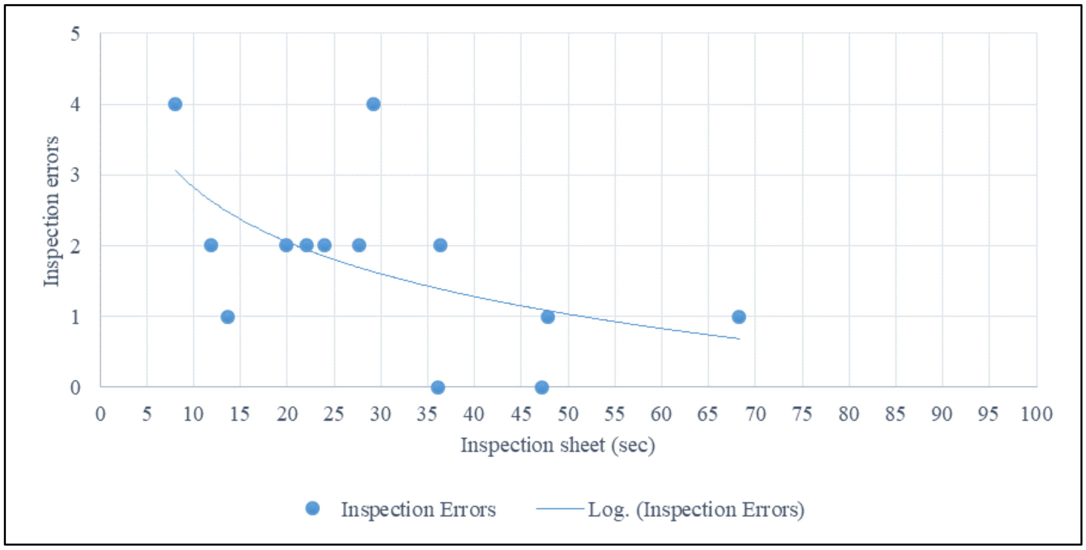


Figure 5-15: Duration of referring to assembly sheet versus number of inspection errors.

Table 5-6: Descriptive statistics summary for Experiment 1 parameters.

Parameters	**Assembly Phase**			**Inspection Phase**		
	N	*M*	*SD*	*N*	*M*	*SD*
Number of Subjects	13			13		
Fixation Duration (ms)		566.9	175.1		990.7	294.2
Normalized Fixation Count (fixations/ms)		6.9	0.8		0.8	0.1
Transition Count (transitions)		78.0	73.9		28.5	8.7
Error count (errors)		2.2	1.0		1.8	1.2
Fixation Duration Variation between Assembly and Measurements (%)		13.0	29.2		-	-

5.5.3 Cognitive Biases Existence in Assembly

One of Experiment 1 goals is to investigate the existence of possible cognitive biases in assembly processes for the inspection phase of production. Preliminary results established the relationship between the occurrence of inspection errors and the inherent cognitive bias that causes them. Assembly processes are behavioral operations. As stated by [14], cognitive biases in behavioral operations can happen at different stages of any operation. Table 5-7 shows the observed cognitive biases in Experiment 1 for the inspection phase and their stage in the work.

Table 5-7: Cognitive biases in Experiment 1, the stage of work where they occur and the resulting inspection errors.

Possible Bias	**Stage in work**	**Error type of inspection that is related to this bias.**
Over confidence	Info processing	- Approves attachments for inspected subassembly. - Approves wrong alignment. - Approves part without inspecting it.
Avoidance of information	Info acquisition	- Not referring to inspection instructions. - Not referring to final product picture. - Incomplete inspection. -Approves assembly although it has a missing part.
Availability	Info acquisition	- Incomplete inspection
Memory bias (recall)	Info processing	- Incomplete inspection

CHAPTER 6

EXPERIMENT 2 METHODS

Experiment 2 was designed according to Experiment 1 results. Experiment 2 represents the implementation stage of the 3-layer model (Figure 1-1). Research methods of this experiment include choosing workplace elements, creating the traditional assistance system, creating the cognitive assistance system, participants, apparatus and stimuli, and experimental procedure.

6.1 Choosing Workplace Elements

Manufacturing workplace is the place where manufacturing goods are manufactured, usually in factories with assembly lines environments. Prior to Experiment 2, workplace elements are chosen based on three considerations. First, the importance of the element for Industry 5.0 requirements. Second, the applicability in a laboratory setting for academia. Finally, the outcomes from Experiment 1 that proposes the most critical variables in the assembly process in I5.0 research.

Figure 6-1 shows the workplace-related elements that are applied in Experiment 2. These elements are prepared for all participants prior to the experiment. Other I5.0 features include monitoring human performance and considering the operator is the center of attention. In addition, I5.0 added features include the inclusion of 3D printing substitution parts that can be used instead of the plastic original parts. The hybrid assembly concept was achieved by using a robot to help assemblers. Higher work complexity is a natural result in Industry 5.0 workplaces. Extra parts and tools are added to the worktable to achieve higher work complexity and using eye-tracking to represent the utilization of new technologies.

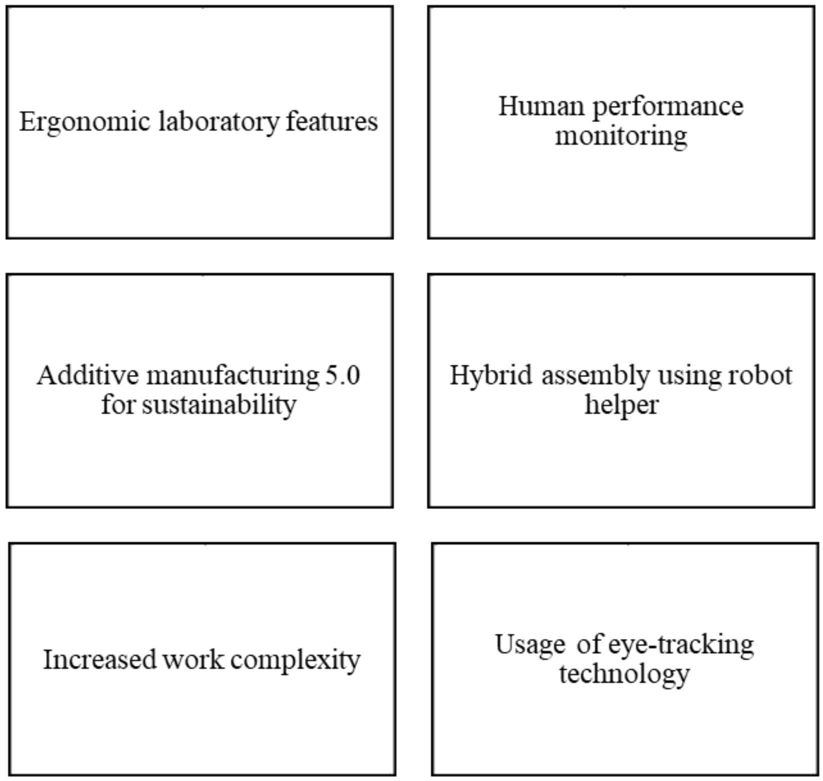


Figure 6-1: Industry 5.0 elements applied in Experiment 2 work environment.

As the quantity and productivity decreases, manual assembly exists. However, it provides high variant diversity and high flexibility. The more quantity and productivity are required, the more automation is suitable, on the expense of product diversity and production flexibility. Hybrid assembly concept combines between the manual assembly and fully automated assembly. Industry 5.0 aims to balance between productivity, quantity, variant diversity, and flexibility, so, it considers the human cognitive judgement, continuous improvement of products and information delivery, smart solutions, and sustainability. Figure 6-2 shows the location of this research work among the different common assembly ways.

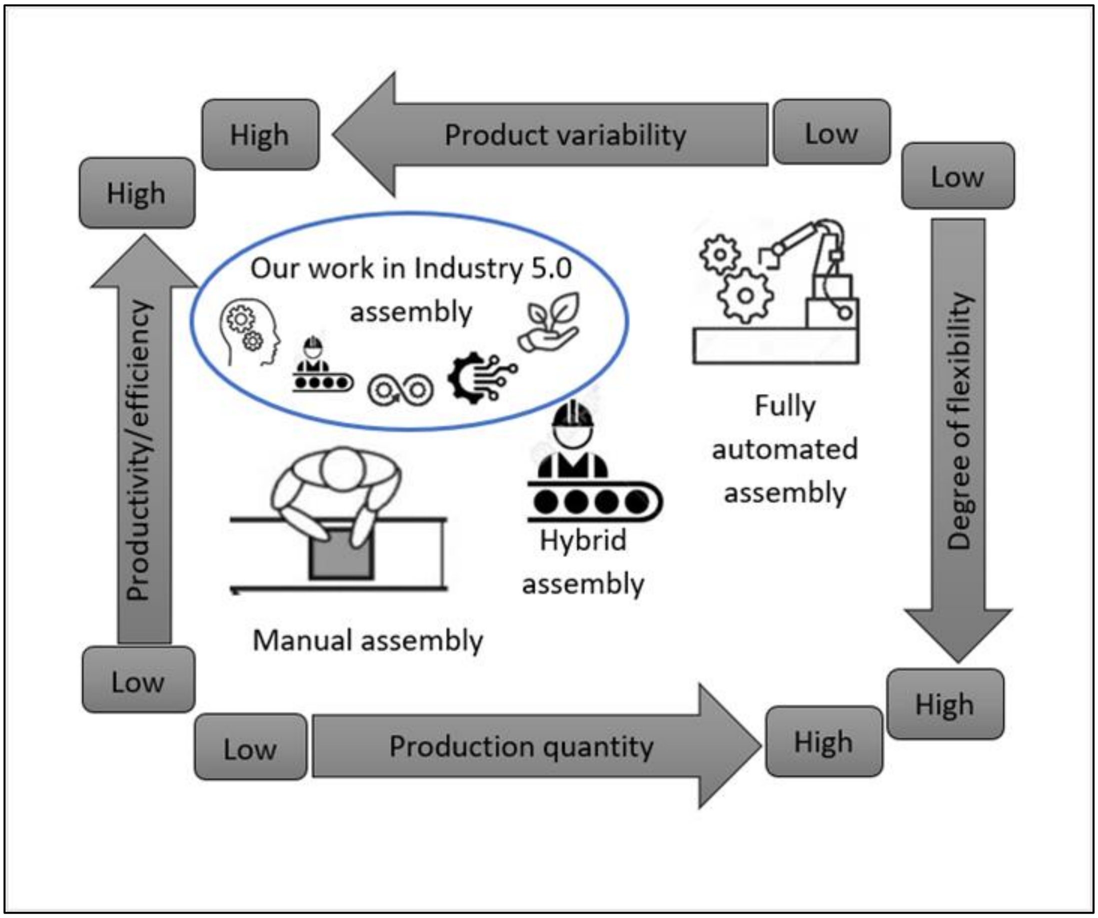


Figure 6-2: Manual assembly, hybrid assembly, fully automated assembly, and our research elements in the Industry 5.0 work environment (based on "Changeable and Reconfigurable Assembly Systems by B. Lotter and H.-P. Wiendahl (2009)") [61].

6.2 The Traditional Assistance System (TAS)

Experiment 2 is a human-centric experiment that aims to investigate human performance in Industry 5.0 work settings. Assisting human in such environment must have a benchmark to compare to. The traditional assistance system (TAS) (Appendix H) was taken from LEGO® and modified to fit the needs of the experiment. It was designed using Microsoft PowerPoint 365® to be familiar to all participants. Mindstorms Robot

Inventor Kit ® is used in the experiment to illustrate assembly tasks. TAS was designed based on LEGO ® building instructions provided by the company in its Lego Mindstorms ® V10.4.0 software. Mindstorms ® is designed specifically by the company for the Mindstorms Robot Inventor Kit 51515 ®. The application provides several features that serves the experimental goal, including:

1. Step-by-step building instructions in the application.
2. 3D models with steps.
3. Helpful tips within coding canvas.
4. Visual coding canvas that can be user-friendly with drag-and-drop feature.
5. The ability to code using Python coding language.
6. Coding elements grouped into categories.
7. More than fifty practice activities.
8. Advance machine learning and a remote-control feature.

During the design process of the TAS, step-by-step directions were added to accommodate the experimental time limits and to stay consistent with the competing CAS. Both assembly directions and coding steps were adopted and redesigned. The system was designed in the modality of consecutive slides provided for participants on a touch screen tablet. No task time display was provided on the system's interface; however, a separate time monitoring screen was provided on the worktable to balance time pressure within the experiment. Figure 6-3 shows the coding interface of Mindstorms© software and an example of traditional system steps as they appear for the user.

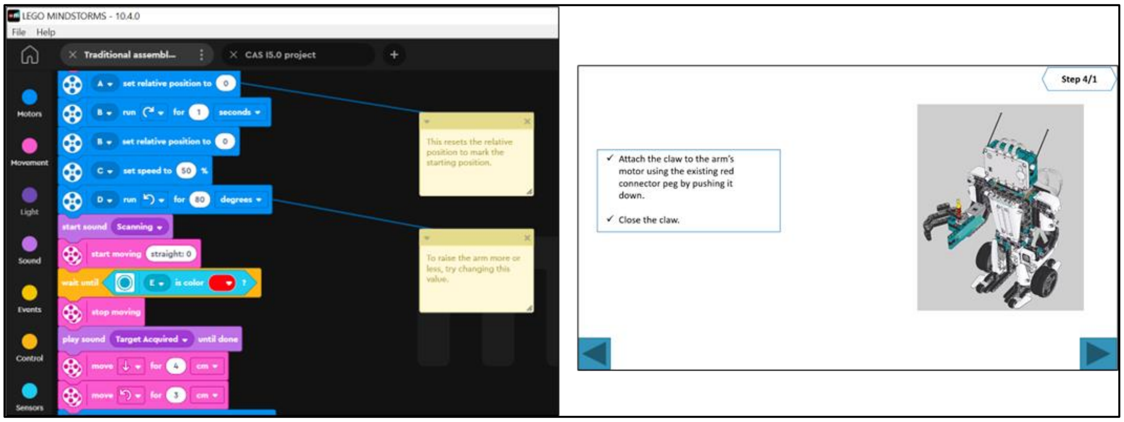


Figure 6-3: Traditional coding interface in Mindstorms® software (left). Traditional system step example (right).

6.3 The Cognitive Assistance System (CAS)

In Experiment 2, a CAS (Appendix I) was tested versus the TAS. The CAS represents an instructional method to guide participants through the experiment in a step-by-step manner. The system was designed on a touch tablet interface using Microsoft PowerPoint 365® to be familiar to all participants (Figure 6-4). The CAS featured task time display (Appendix J), video instructions, cognitive biases resolving tips, text instructions, graphical instructions, direction clue arrows, safety warnings, end-of-task reminders, and priority instructions.

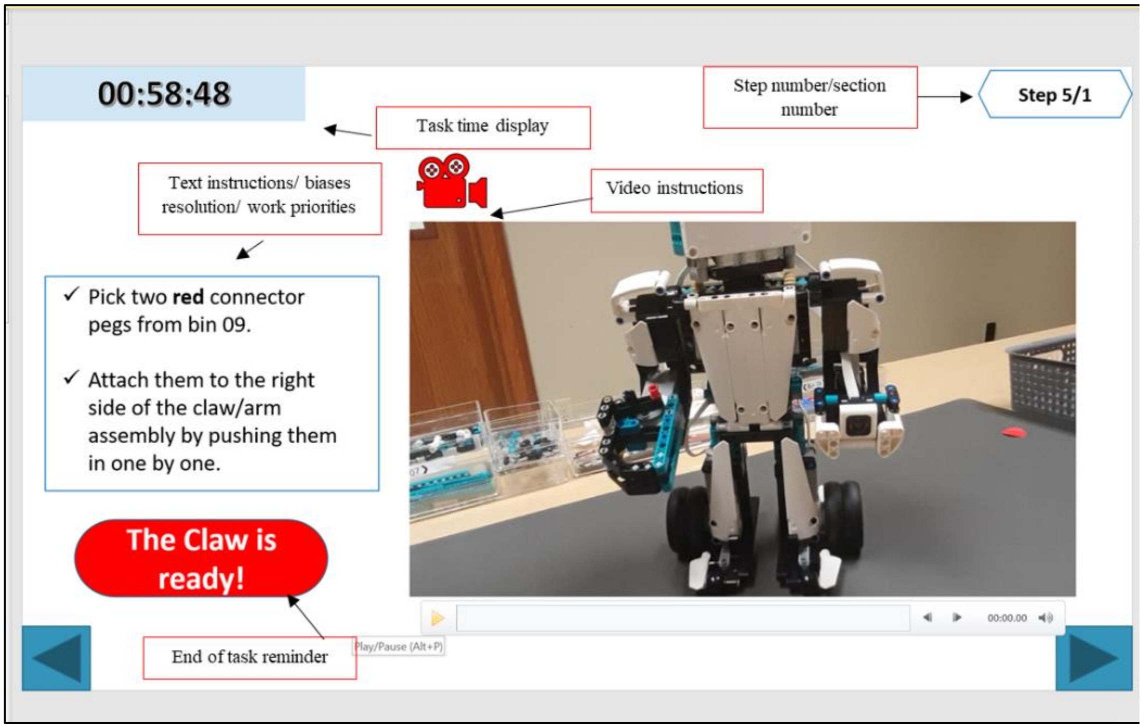


Figure 6-4: The cognitive assistance system interface elements.

Table 6-1 shows a comparison between the TAS and the CAS features. This table describes the comparison criteria between the two systems in terms of technical features on both interfaces.

Table 6-1: Comparison between the traditional assistance system and the cognitive assistance

Comparison criteria	**TAS**	**CAS**
Has WIP	no	yes
Video Instructions	no	yes
Video of Code And Automation Inspection	before the actual task	after the actual task
Text Instructions	yes	yes
Graphics	no	yes
3D Models	yes	yes
Color Clues	no	yes
Direction Clues	no	yes
Indicate Priorities	no	yes
Time Display	no	yes
Pictures	yes	yes
Information Alerts	no	yes
Safety Warnings	yes	yes
Highlight Important Clues	no	yes
Coding Clues	yes (originally from Mindstorms app)	yes
Text Tips Sticky Notes	yes (originally from Mindstorms app)	no

6.4 Experiment Design and Variables

Participants were assigned the assistance system type, alternating, to achieve equal group sizes. The dependent variables include measures of CL and bias and include fixation duration, normalized fixation count, NASA-TLX, and error count. In addition, the CRT test (Appendix G) was administered to determine additionally whether this impacted cognitive biases.

Table 6-2 shows Experiment 2 variables, their types, and their measurements. The independent variables are the thinking style and the user satisfaction. Thinking style was measured using the expanded 7-question CRT. In addition, user satisfaction was measured using the PSSUQ. The experimental dependent variables are the CL and cognitive bias human performance. CL was measured using subjective and objective methods. The subjective scoring method was the NASA-TLX, whilst the objective method was the eye-tracking data. Fixation duration and fixation count measures were used as objective measures for CL. Finally, the cognitive bias human performance was assessed and measured using the bias-related error count.

Table 6-2: Experiment 2 variables and their corresponding measures.

Type	**Variable**	**Measure**
Independent	System Type	TAS or CAS
	Thinking Style	Cognitive Reflection Test (CRT)
Dependent	Cognitive Load	Fixation duration (ms) (*objective*)
		Normalized fixation count (fixations/ms) (*objective*)
		NASA-TLX (*subjective*)
	Cognitive Bias Human Performance	Bias-related error count
	User Satisfaction	Post Study System Usability Questionnaire (PSSUQ)

6.5 Participants and Task Design

Power analysis were conducted to estimate the number of subjects (Figure F-7 to Figure F-16). The study comprised 26 participants, 5 females and 21 males. The participants were recruited from the college community. Twenty-five subjects have had previous experience with SOLIDWORKS© software. Twenty-two subjects have had previous experience with the 3D-printing process. The experiment comprised four tasks and four inspections (Figure 6-5). The subjects were volunteers and were not paid for participating. Prior to participating in the study, informed written consent was obtained from each subject and brief training was provided for each subject. This study conformed to the Louisiana Tech University Internal Review Board (IRB).

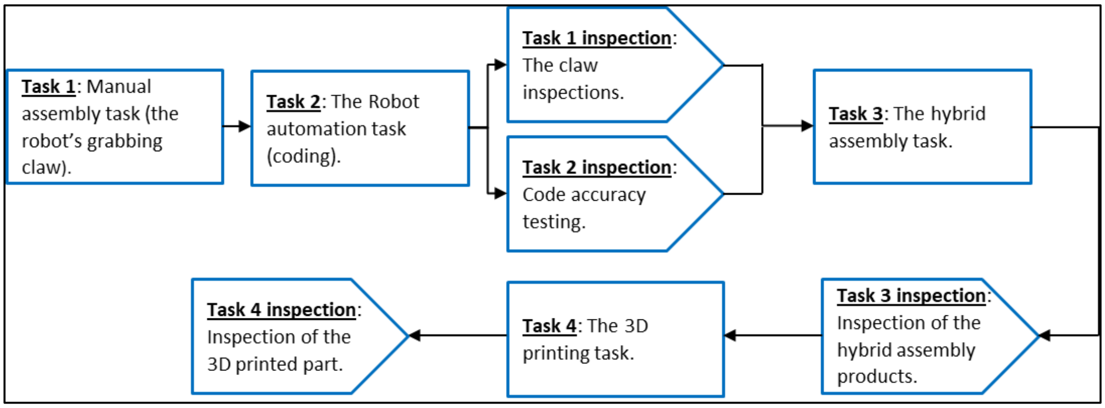


Figure 6-5: Experiment 2 tasks and tasks inspections sequence.

6.6 Apparatus and Stimuli

Pupil Core wearable eye tracker from Pupil Labs [60], was used to record the visual behavior of assemblers. The eye-tracking glasses were connected to a PC with Windows 10 operating system via USB. It was running with Pupil Capture v3.4.0 desktop software that enabled real-time data capturing and recording. The ergonomic design of the laboratory workplace includes adjusted light, adjustable chair, and ergonomic mouse. The distance between the assembler and the PC workstation was 40 inches to help assembler in reaching the PC workstation and turning back to other workstations and the assistance system. The workplace comprised four main workstations, the assembly workstation, the PC workstation, the 3D printing workstation, and the robot workstation (Figure 6-6). The assembly workstation comprised pre-organized work bins labeled sequentially. In addition, assembly workstation featured a work in process (WIP) and scrap station. The designated assistance system (TAS or CAS) was pre-downloaded on the touch tablet and placed on the worktable for the participants as of their choice of convenience. The tablet comprised two main screens that the assemblers switch from and to. The first screen was the coding software, and the second screen was the assistance system.

The PC workstation had all the required software that the assembler would use during the tasks. The 3D printing workstation was prepared and placed on the right side of the assembler within reach distance. The robot workstation was placed in the middle of the worktable so the robot can have sufficient space to move and help in the assembly process.

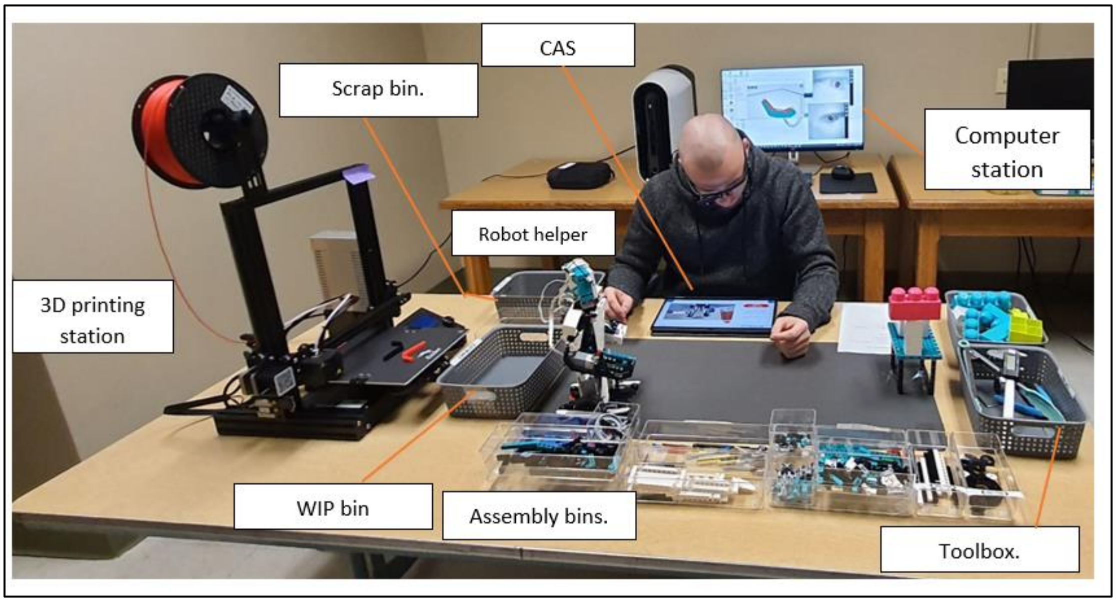


Figure 6-6: Experiment 2 workstations: the assembly workstation, the PC workstation, the 3D printing workstation, and the robot workstation.

6.7 Pre-experiment

Prior to Experiment 2, each participant was given a briefing on the tasks nature, eye-tracking technology, calibration process, Industry 5.0, and time limit. A short training (Appendix N) was provided to the participants to familiarize them with the technical requirements of the used devices. However, no information was given during the training about the task's steps and specifications. This time limit included filling out a consent form, answering a pre-experiment questionnaire (Figure E-5), answering the tests and surveys, calibrating the eye-tracker, and finishing the tasks. During the calibration process, the eye-tracker was adjusted based on each participant's face and head features. The world camera was adjusted in a rotational movement for the best capture of the assembly work angel in front. It was calibrated for focus for the best recording clarity. Eyes cameras were adjusted for each participant in a back-and-forth movement for the best pupil capturing during the assembly process. The glasses were calibrated using a 5-point calibration on-screen method for each participant using a 3D eye model.

6.8 The CRT Test

The cognitive reflection test (CRT) [62] is a test that measures the ability to perceive an incorrect response alternative and applies further reflection to find the correct response. In this experiment, the expanded version of the CRT test [63] was used to measure the thinking style of participants to evaluate whether they possess a deliberate thinking style or intuitive thinking style.

6.9 Assistant Systems and Assembly Tasks

All the tasks were explained and labeled clearly in both systems. The laboratory was dedicated to each participant for the experiment. Participants needed to complete the four tasks within the one-hour time limit and with no breaks. Participants could not ask questions. Tasks were organized on the assistant system in a consecutive order. Participants could switch from one slide to another to follow the steps. Participants could switch back and forth between the coding software and the assistant system. However, once the time limit was over, the system stopped automatically.

The experiment had two systems, the TAS and the CAS. During the training, participants were given enough information to use the system, so they don't face any technical issues during the task time. However, all participants were blind that there are two competing systems to accomplish the tasks. All tasks' requirements were the same in both systems.

6.9.1 Task 1: Manual Assembly Task

Task 1 was a basic manual assembly task without automation or tools. In Task 1, participants were required to assemble the robot's claw that was fixed on the robot's arm and inspect it. They followed a step-by-step instructions according to which system they are using (TAS or CAS). Participants were required to reach and extract parts from the numbered bins to complete the task. They needed to check parts names to be consistent with the company's original parts list provided within both systems. The experimental steps included requirements that could apply extra CL on assemblers, such as alignment, color, direction, shape, priority, and force. Motors represented an important part of Task 1. Assemblers needed to relate the motor alphabetical reference label in the coding software to its physical location in the assembly. They were required to monitor motors accuracy simultaneously in the software.

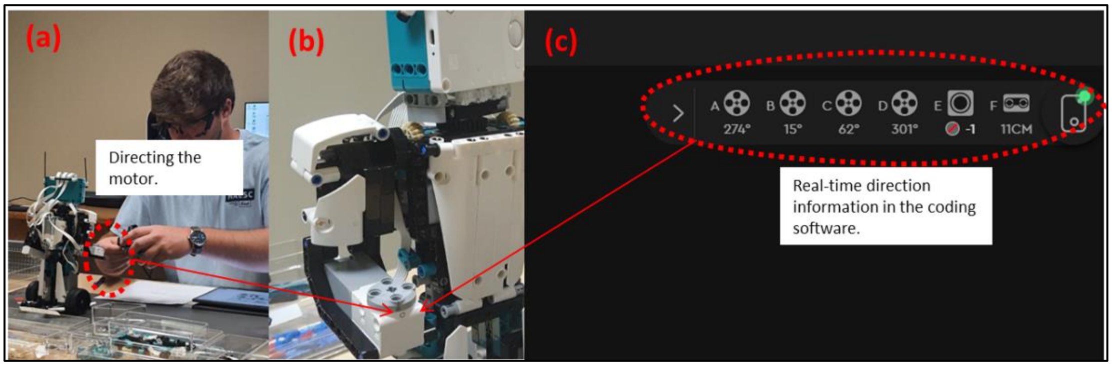


Figure 6-7: Manual assembly of the robot's claw. (a) Assembler directing the motor in the specified degrees. (b) Enlarged view of the arm's motor in the zero direction. (c) Real-time positioning data which the assembler monitors simultaneously in Mindstorms® software.

6.9.2 Task 2: The Robot Automation Task

In this task, each participant changed a prepared code under a project that was titled specifically for the assembler's group. Coding requirements included adding, removing, and editing code lines. The steps in this task included clues for coding, such as code group color (Appendix O). Moreover, the assembler was required to check project's name and download the code on a specified memory slot within the robot. At the end of this task, the robot was automated and ready to be used for Task 3 (the hybrid assembly).

6.9.3 Task 1 Inspection

In this task, the assembler was required to inspect the robot's claw that was assembled in Task 1. The inspection of this task required the assembler to check whether the assembled claw was securely fixed on the robot's arm and to record their inspection results in the provided inspections sheet.

6.9.4 Task 2 Inspection

In this task, the assembler had to execute the code and test its accuracy. As a result, the robot moved from the instructed position to the subassemblies location, grab subassemblies, and place them in the WIP bin. The assembler role was to place the robot accurately in the instructed position, execute the code and observe the activity results. If the robot failed to place subassemblies in the WIP bin, the assembler had to scrap them in the designated scrap bin. In either case, the assembler should record the inspection activity results in the inspection sheet. Automation outcomes and success criteria are summarized in Figure 6-8.

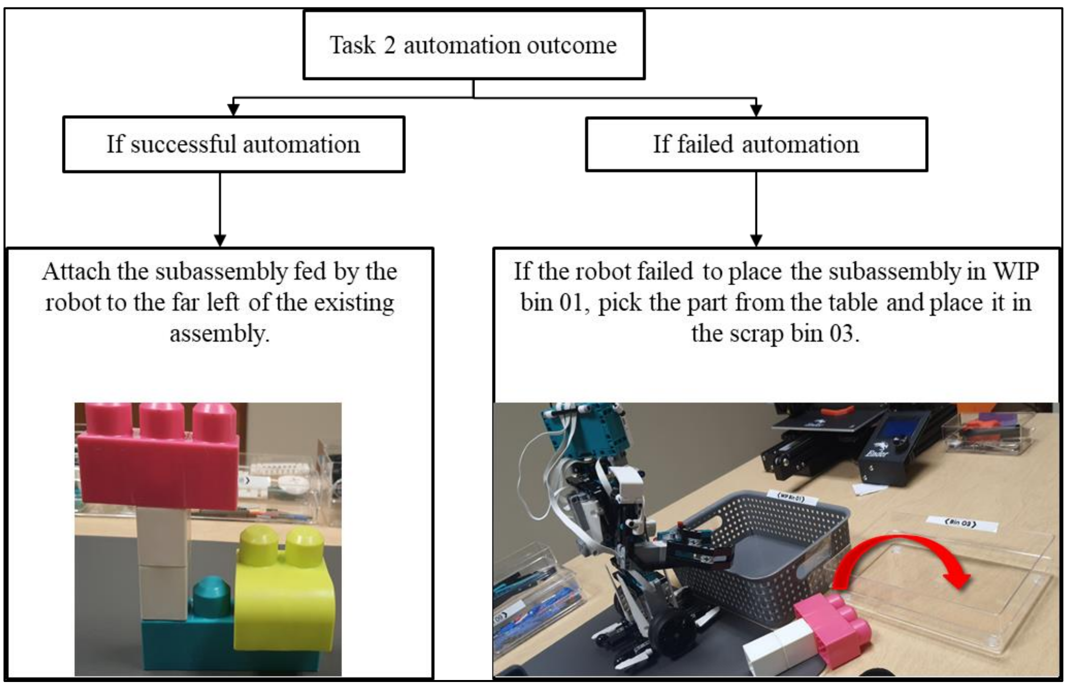


Figure 6-8: Task 2 automation outcomes.

6.9.5 Task 3: The Hybrid Assembly Task

In this task, the assembler was required to build several designs of building blocks. They had to find correct bins, and produce the correct design specifications. Design specifications instructed by the system included parts size, count, direction, and shape features.

6.9.6 Task 3 Inspection: The Hybrid Assembly Products Inspection

Following Task 3, the assembler had inspect the end-products for several criteria such as thickness, colors, shapes and directions to record the resulting judgement in the inspections sheet. The Assembler needed to make sure that the parts comply with the size specifications using measurements tools. Finally, the assembler had to record the required measurements in the measurement sheet (Appendix K).

6.9.7 Task 4: The 3D Printing Task

In this task, the assembly followed the system's steps to change a pre-designed LEGO® Mindstorms double-angled building block design. SOLIDWORKS® and Creality® software were used to perform the 3D printing. The part was a replica of the original part and could be used in the robot to substitute the original part as a green solution. Figure 6-9 shows the original part versus the 3D printed part.

Figure 6-9: LEGO double-angled beam (black). The experiment substitution 3D-printed double-angled beam (red).

6.9.8 Task 4 Inspection: Inspection of the 3D-printed Part

In the last step, the assembler followed the system's steps to inspect the 3D-printed part and make sure that it was within size specifications using measurement tools. Finally, the assembler recorded the measurements in the measurements sheet and exited the system.

6.10 NASA-TLX TEST

Hart and Staveland's National Aeronautics and Space Administration Task Load Index (NASA-TLX) method measured the CL resulting in experimental A5.0 tasks. The CL is represented on six 7-point scales with increments of high, medium and low.

NASA-TLX is considered a subjective CL assessment tool. It has been originally used in civil and military aviation [64]. Using NASA-TLX has been expanded to other fields as a subjective measure of CL and task complexity. It was combined with eye-tracking technology to support other measures, as in food industry study [37], manual assembly study [65], and construction [52]. In manufacturing, it has been used as a supportive measure to study the effect of cognitive aspect in manual assembly [22], in safety assessment, and design of automated systems [66]. The NASA-TLX uses a multi-dimensional scale to measure operator task performance, which comprises six subscales:

1. Mental Demand: How mentally demanding was the task?

2. Physical Demand: How physically demanding was the task?

3. Temporal Demand: How hurried or rushed was the pace of the task?

4. Performance: How successful were you in accomplishing what you were asked to do?

5. Effort: How hard did you have to work to accomplish your level of performance?

6. Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?

Directly after finishing the tasks, assemblers answer the NASA-TLX items using the paper version of the test. The interval scale (Appendix L) rates the six categories on a scale from 0 to 100, where 0 symbolizes the lowest task load and 100 is the highest task load.

6.11 The IBM Post Study System Usability Questionnaire (PSSUQ)

Research reviewed the importance of using questionnaire methods for usability assessment [67]. Tens of standardized usability questionnaires were prepared to measure user satisfaction with software interfaces [68]. PSSUQ (Appendix M) is free to use, can be generalized, flexible, and has a high overall reliability of 0.96 [69]. The questionnaire comprises 19 items featuring Likert Scale (LS) type. The items are split into four subcategories:

1. System usability (SYSUSE): covered by items 1 through 8 and assesses the usability of the system for the devoted purpose.

2. Information quality (INFOQUAL): covered by the items 9 through 15 and assesses the quality of information provided by the system.

3. Interface quality (INTERQUAL): covered by the items 16 through 18 and assesses the quality of the interface of the system.

4. Overall quality (OVERALL): item 19 of the questionnaire that assesses the overall quality of the system elements.

In this experiment, PSSUQ was used to collect feedback about systems interfaces to improve the CAS design and apply the continuous improvement concept.

CHAPTER 7

EXPERIMENT 2 RESULTS

This section states the findings of Experiment 2 based on the information gathered through the applied methods, Hypotheses and Systems comparison

Hypotheses were established for Experiment 2 to test the significance of experimental parameters on the results. The research questions and their corresponding hypotheses are summarized in Table 7-1.

Table 7-1: Experiment 2 research questions and their corresponding hypotheses (CL: 95%, α: 0.05).

No.	Research question	Hypotheses
1	Will the system type impact CL?	H_0: System type will have a significant impact on the CL? H_1: System type will not have a significant impact on the CL.
2	Will using the cognitive assistance system improve the user satisfaction?	H_0: The CAS will have a significant effect on the user satisfaction compared to TAS. H_1: The CAS will not have a significant effect on the user satisfaction compared to TAS.
3	Will using the cognitive assistance system reduce cognitive bias-related assembly errors?	H_0: The CAS will have a significant effect on assembly error count compared to TAS. H_1: The CAS will not have a significant effect on assembly error count compared to TAS.

7.1 Data Extraction

During the experiment, the eye real-time eye movements of participants were recorded. Data was analyzed using iMotions-v9.3.13 software. Data was obtained by converting participant's real-time recording from the Pupil Capture v3.4.0 software to iMotions-compatible recording.

7.2 Thinking Style

Thinking style was assessed using the expanded 7-question CRT. The results of the CRT test for the TAS and the CAS are shown in Figure 7-1 and Figure 7-2, respectively.

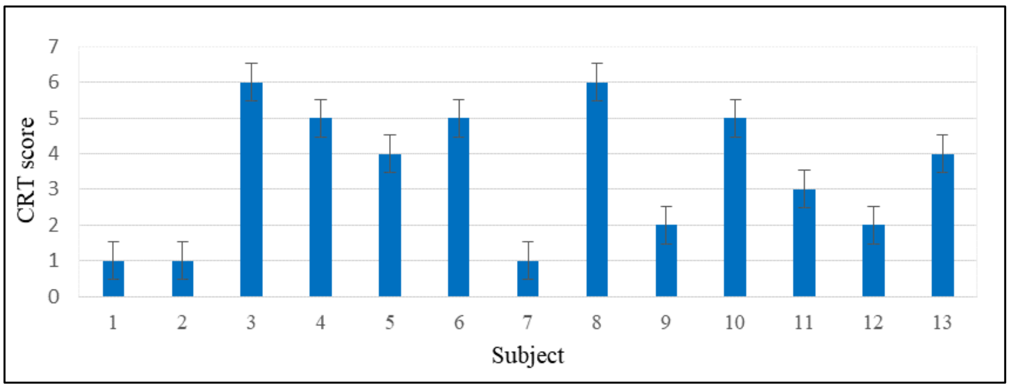


Figure 7-1: CRT scores for subjects with the TAS.

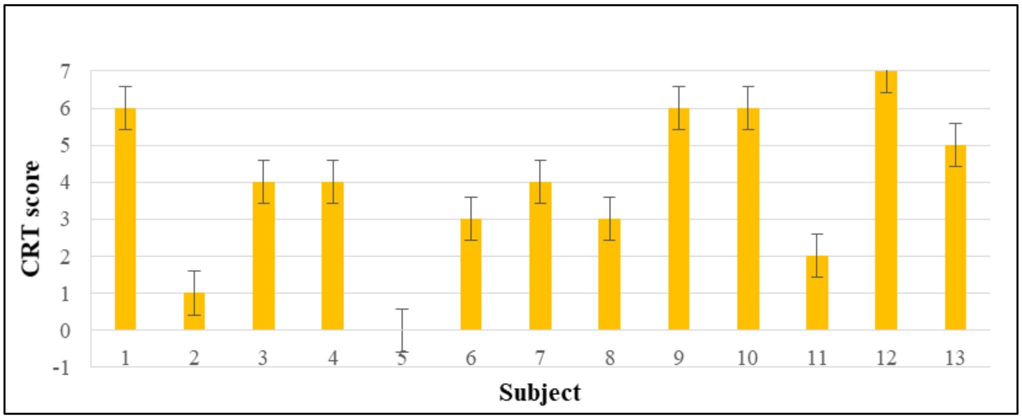


Figure 7-2: CRT scores for subjects with the CAS.

7.3 Cognitive Load

Figure 7-3 shows fixation duration for CAS compared to TAS.

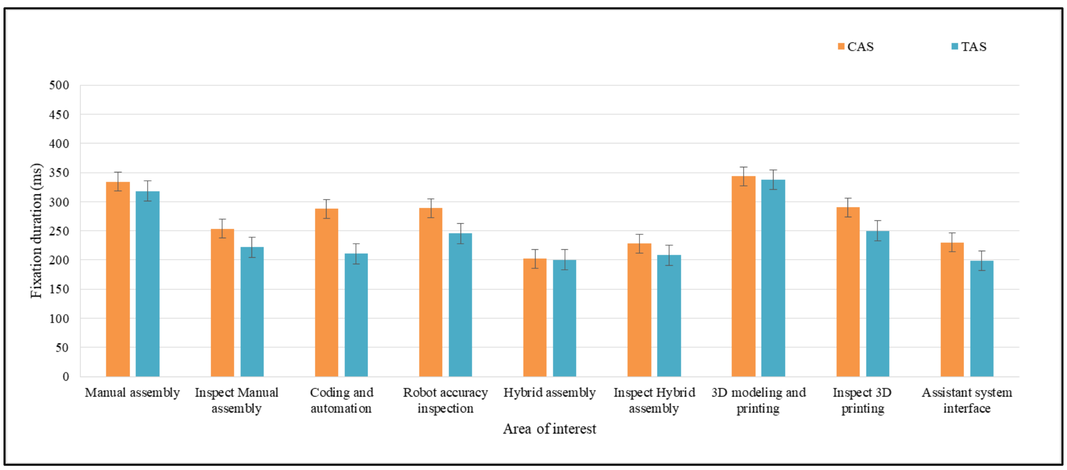


Figure 7-3: Fixation duration for the TAS versus CAS for each AOI.

The fixation duration on the CAS and TAS interfaces are shown in Figure 7-4.

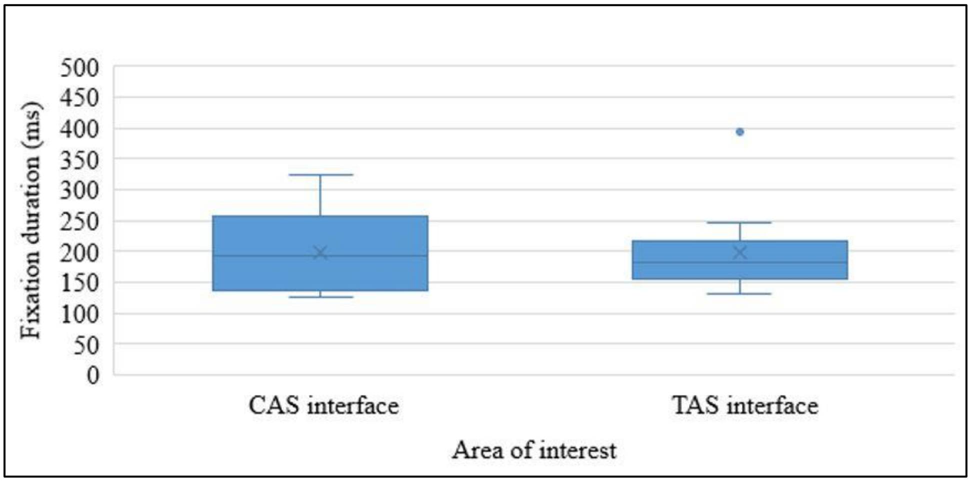


Figure 7-4: Fixation duration on the CAS and TAS interfaces.

Figure 7-5 shows the normalized fixation count for the CAS and TAS users on each AOI.

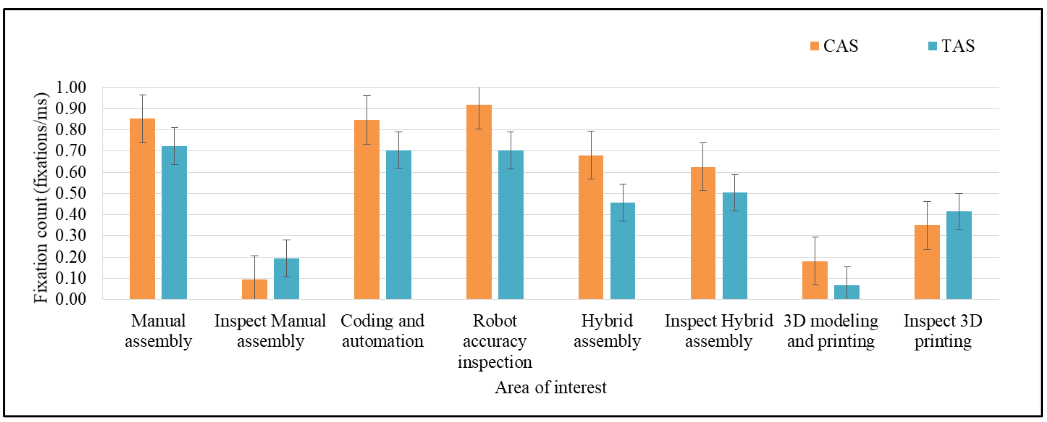


Figure 7-5: Normalized fixation count for the CAS and the TAS.

Figure 7-6 shows the normalized fixation count for the CAS and TAS users on each AOI.

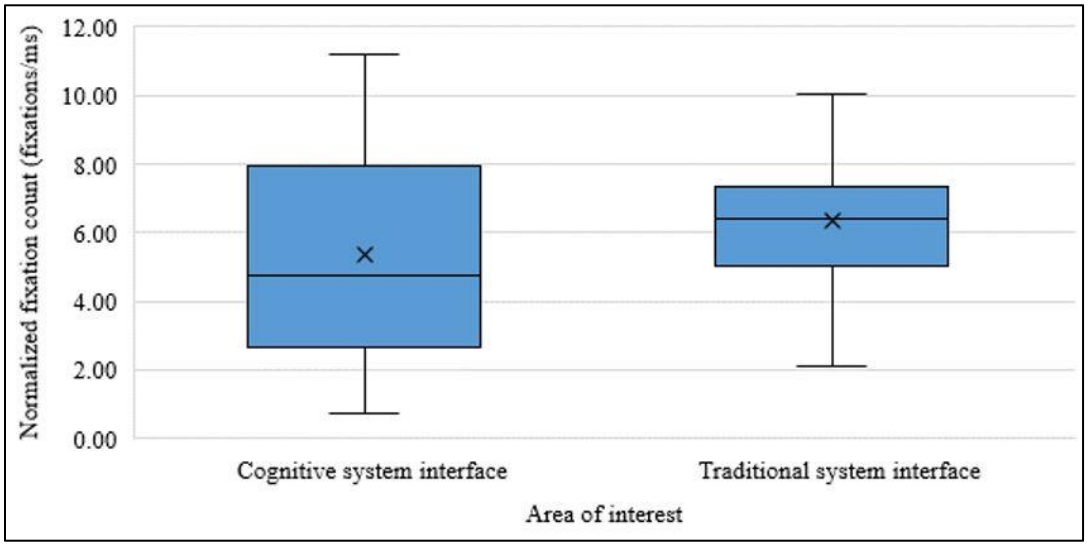


Figure 7-6: Normalized fixation duration on the system interface for the CAS and the TAS.

Figure 7-7 and Figure 7-8 show the NASA-TLX scores for the TAS users versus the CAS users for an in-between subject experiments.

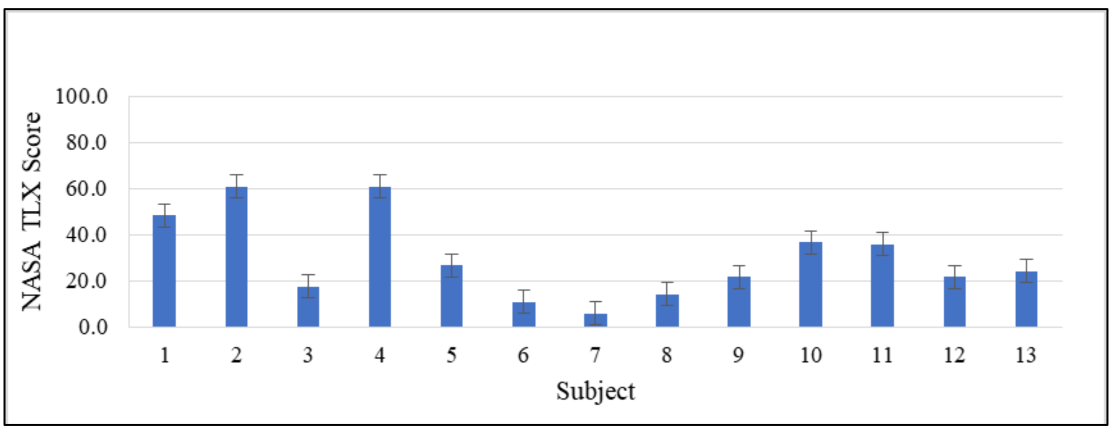


Figure 7-7: NASA-TLX scores reported by TAS users.

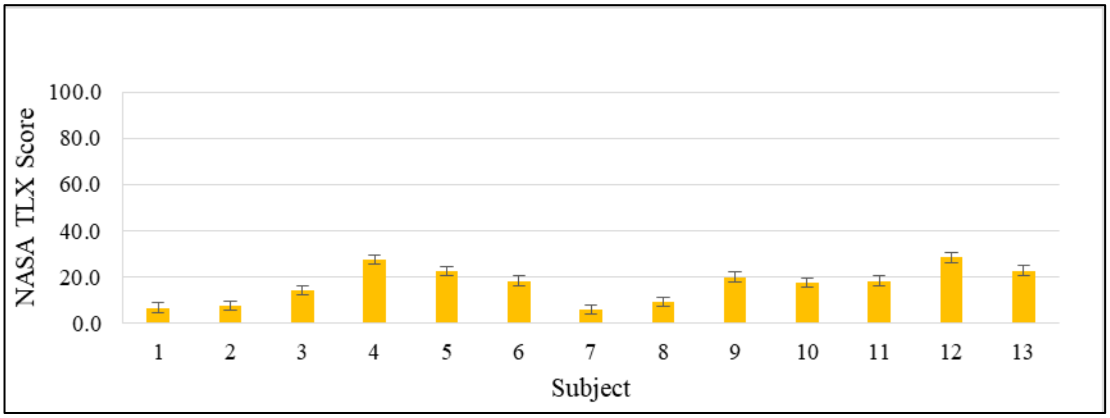


Figure 7-8: NASA-TLX scores reported by CAS users.

Figures Figure 7-9 and Figure 7-10 show the subcategories scores for NASA-TLX scores for the TAS and the CAS.

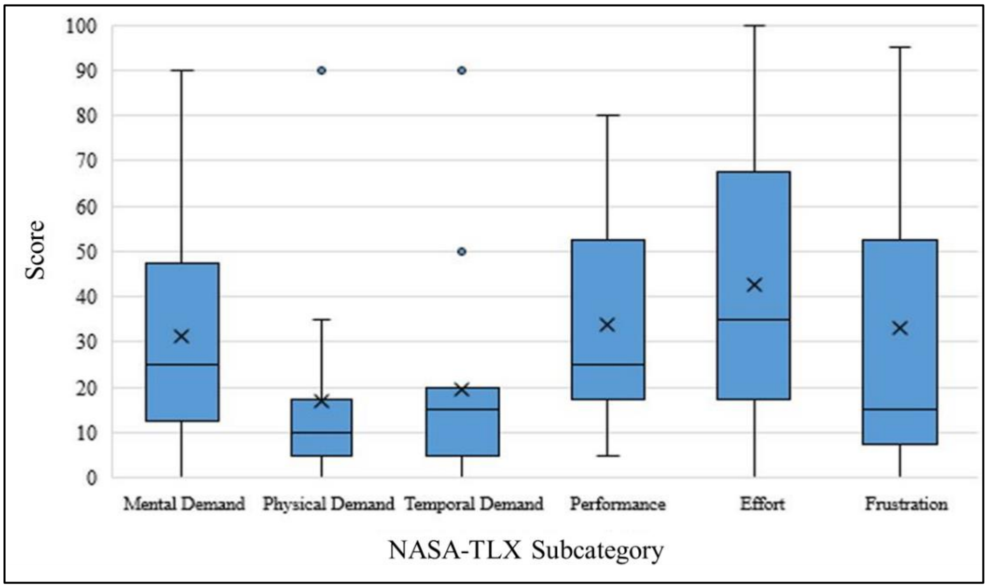


Figure 7-9: NASA-TLX score subcategories scored for the TAS.

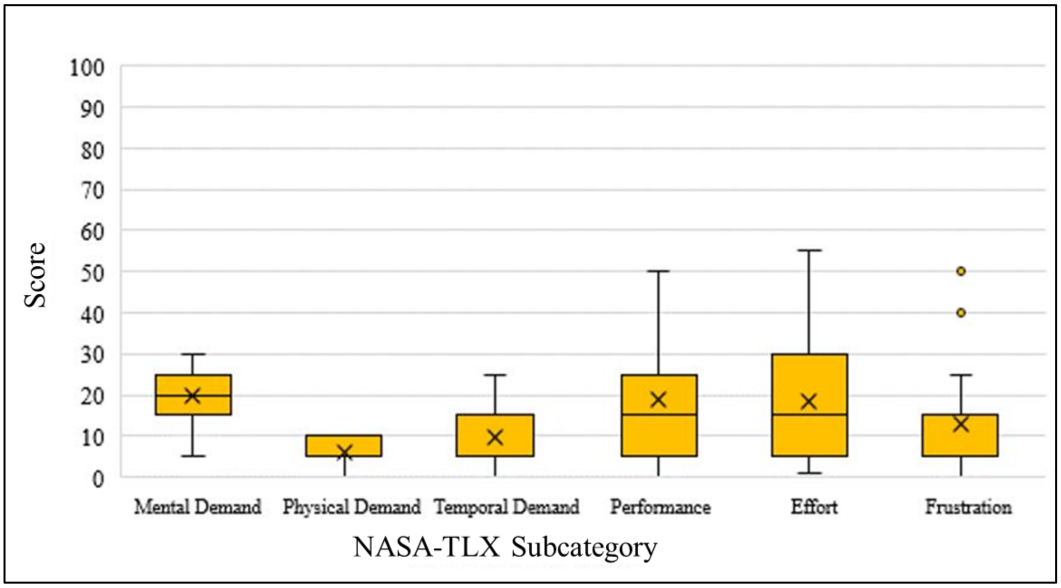


Figure 7-10: NASA-TLX score subcategories scored for the CAS.

7.4 Cognitive Bias (Human Performance)

Two types of cognitive biases were investigated, avoidance of information and overconfidence. Biases occurrences classified based on the stage of assembly work. The avoidance of information is observed during information acquisition, while overconfidence is observed during information processing. Experiment 2 cognitive biases, their stage in work and the related error types in assembly tasks are summarized in Table 7-2. Avoidance of information related errors includes not using the safety tools, ignoring to scrap parts if automation fails, unnecessary repetitions, wrong coding, defective product, wrong 3D modeling, and ignoring a step. Overconfidence related errors include not inspecting a part correctly and recording pass for a failure.

Table 7-2: Experiment 2 cognitive biases, stage in work of which they occur, and the bias-related assembly tasks.

Cognitive bias	**Stage in work**	**Bias-related assembly error**
Avoidance of information	Information acquisition	not using the safety tools
		Not scrapping parts if automation fails
		unnecessary repetitions
		wrong coding
		defective product
		wrong 3D modeling
		ignoring a step
Overconfidence	Information processing	Wrong parts inspection technique

The results for bias-related error count are shown in Figures 7-11 to 7-14.

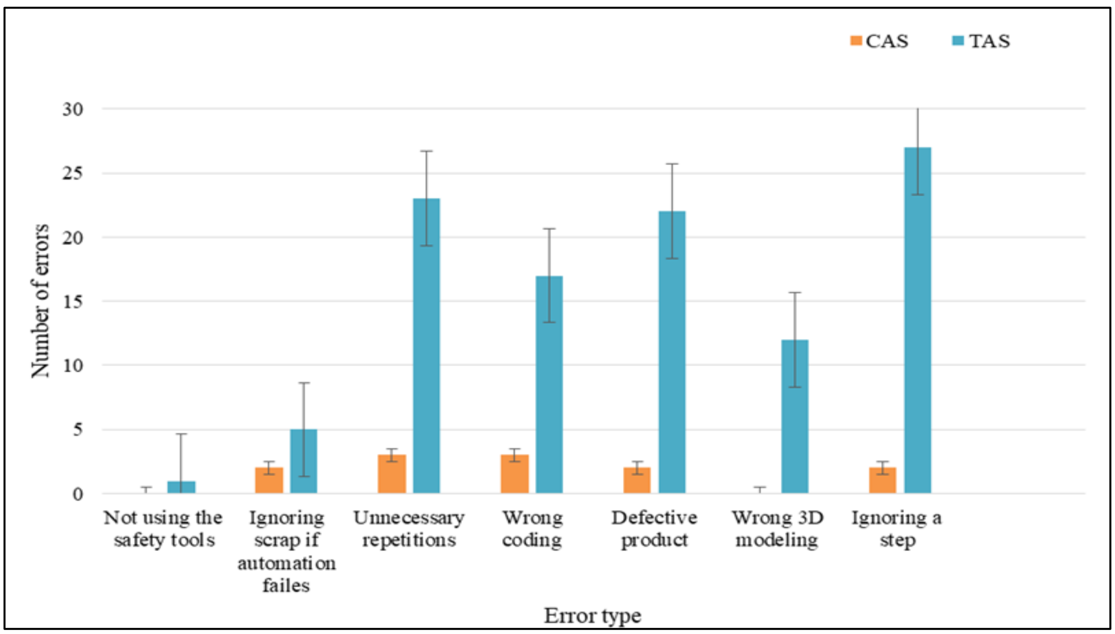


Figure 7-11: Avoidance of information bias-related errors in assembly tasks for the CAS and the TAS.

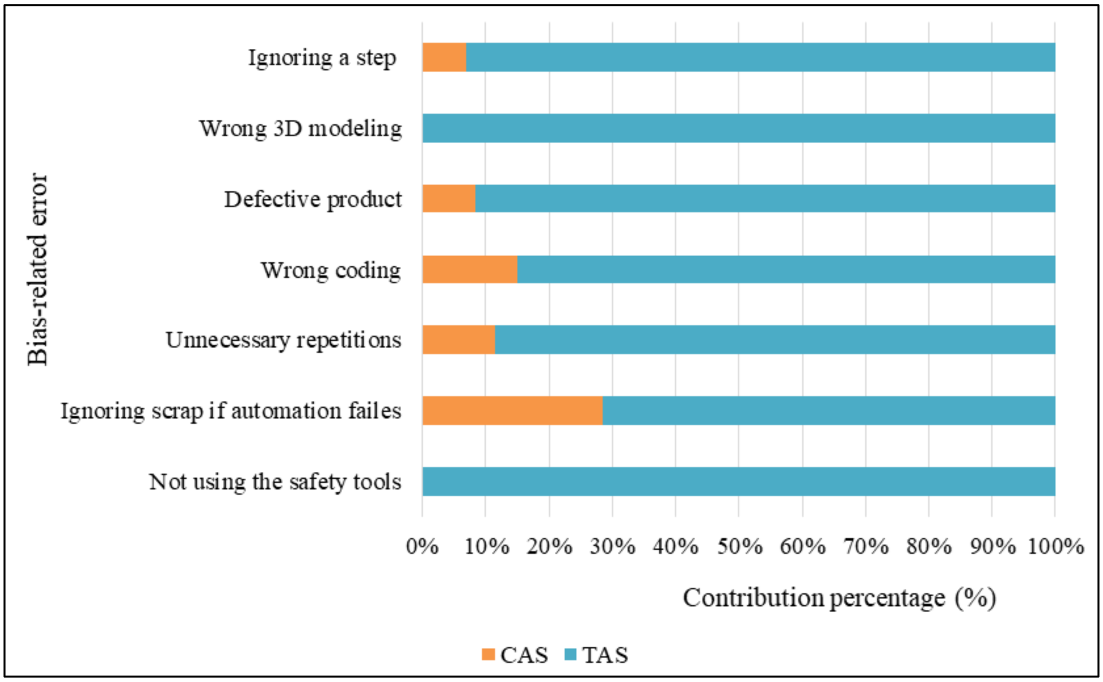


Figure 7-12: Avoidance of information bias error contribution percent for the CAS and the TAS.

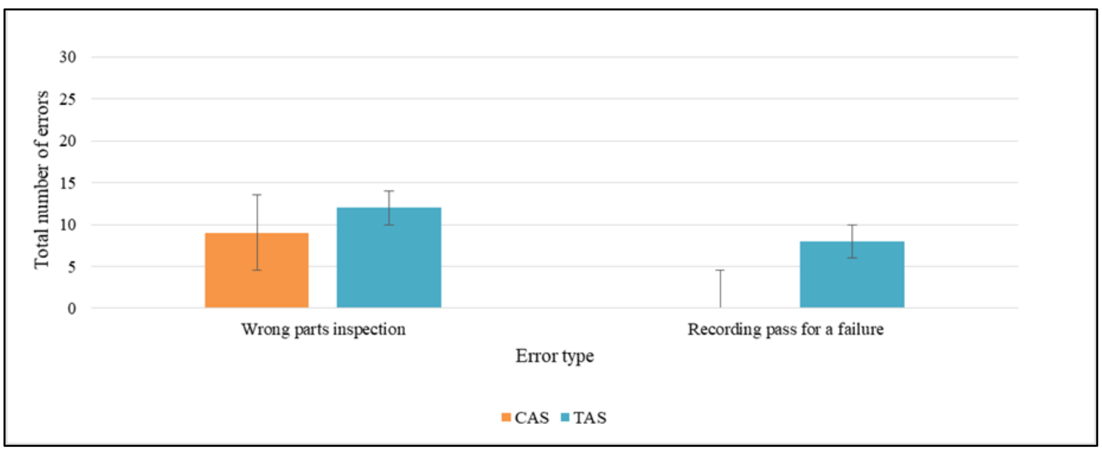


Figure 7-13: Overconfidence bias-related errors in assembly tasks for the CAS and the TAS.

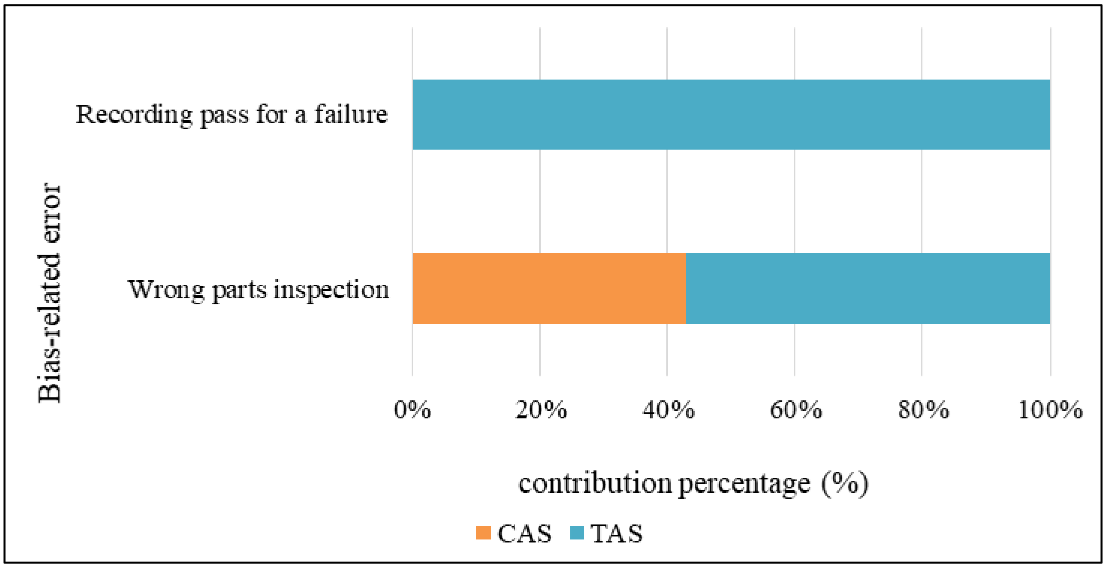


Figure 7-14: Overconfidence bias-related error contribution percent for the CAS and the TAS.

7.5 User Satisfaction

User satisfaction for the TAS and CAS users was assessed using the PSSUQ. Figure 7-15 to Figure 7-18 show the scores for TAS users and CAS users in terms of overall satisfaction (OVERALL), system usability (SYSUSE), information quality, (INFOQUAL), and interface quality (INTERQUAL).

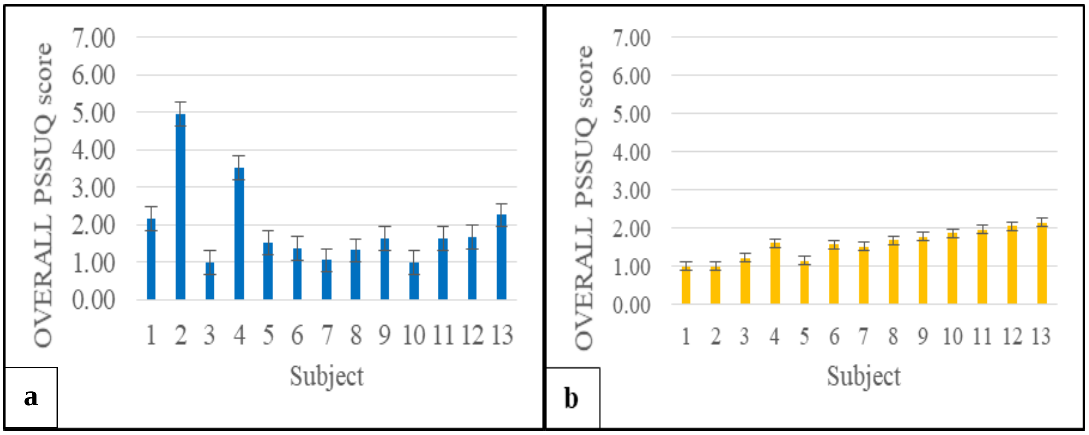


Figure 7-15: User satisfaction measured by PSSUQ scores for the Subcategory OVERALL. (a) TAS (b) CAS.

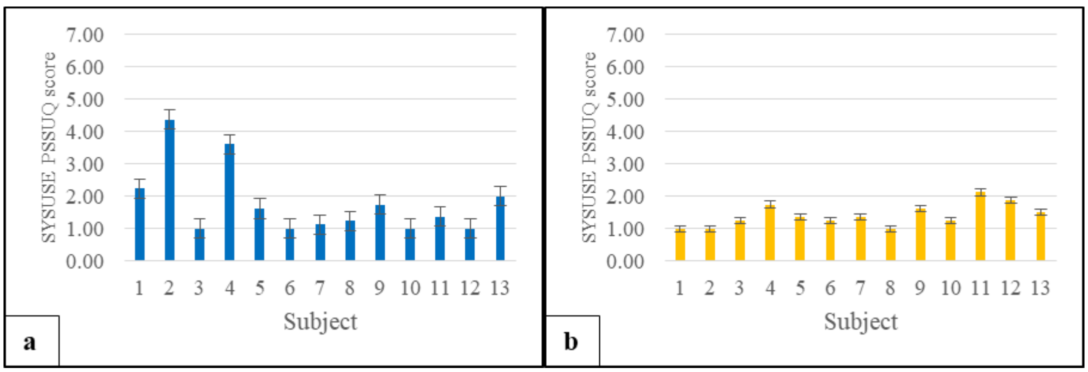


Figure 7-16: Figure 4 30. User satisfaction measured by PSSUQ scores. For the SYSUSE subcategory. (a) TAS (b) CAS.

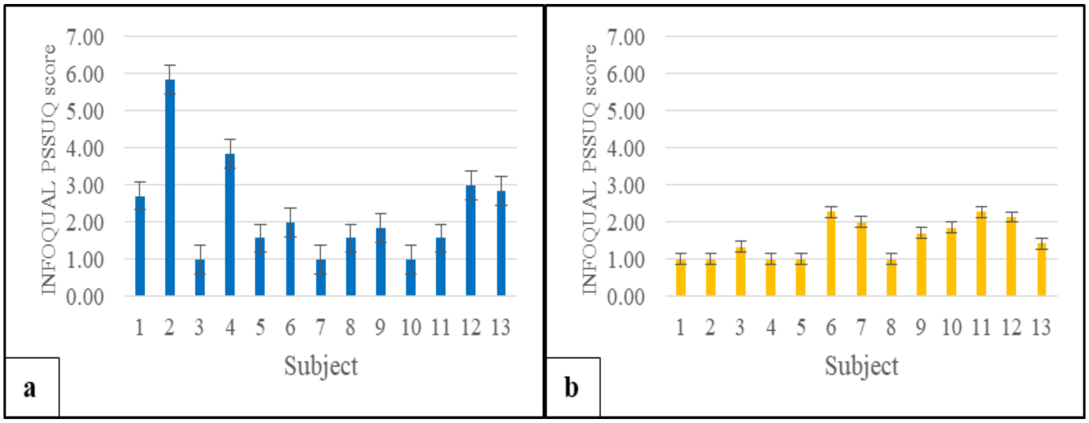


Figure 7-17: User satisfaction measured by PSSUQ scores. For the Subcategory INFOQUAL. (a) TAS (b) CAS.

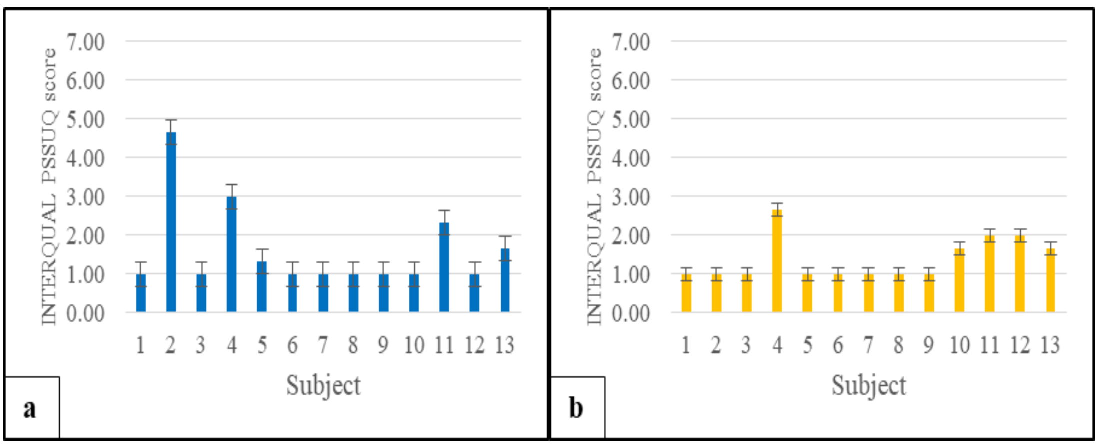


Figure 7-18: User satisfaction measured by PSSUQ scores. For the Subcategory INTERQUAL. (a) TAS (b) CAS.

In summary (Table 7-3), descriptive statistics, showed that the mean CRT score for the TAS users group was (M=3.46) while the mean CRT score for the CAS users was (M=3.92). For the fixation duration variable, the maximum fixation duration in the TAS group was 492.87 (ms) while the maximum fixation duration in CAS group was 402.91. The normalized fixation count for TAS users was almost equal to the CAS group users with 1.12 (fixation/ms) and 1.14 (fixation/ms), respectively. Users of TAS submitted an average NASA-TLX score of 29.61 while the users of CAS submitted an average NASA-

TLX score of 16.79 (43% less). The maximum NASA-TLX score for TAS users was 60.83 while the maximum score for CAS users was 28.33. The maximum bias-related error count for the TAS users was 28 errors. However, the maximum bias-related error count for the CAS users was 7 errors. Finally, the average user satisfaction score for TAS users was 1.92 while it was 1.44 (less score means better performance on the PSSUQ scale).

Table 7-3: Summary descriptive statistics of the traditional assistance system (TAS) and the cognitive assistance system (CAS).

Parameters	**TAS**					**CAS**				
	N	*M*	*SD*	*Max*	*Min*	*N*	*M*	*SD*	*Max*	*Min*
Number of Subjects	13					13				
CRT		3.46	1.89	6.00	1.00		3.92	2.10	7.00	0.00
Fixation duration (ms)		243.49	82.98	492.87	156.82		250.39	81.97	402.91	140.29
Normalized fixation count (fixations/ms)		1.12	0.33	1.62	0.39		1.14	0.59	2.07	0.30
NASA-TLX		29.61	17.92	60.83	5.83		16.79	7.65	28.33	5.83
Bias-related error count		9.76	8.00	28.00	2.00		1.61	1.80	7.00	0.00
OVERALL-PSSUQ		1.92	1.13	4.94	1.00		1.44	0.35	2.10	1.00

The correlations between the thinking style (Deliberate/Intuitive) measured by the CRT and the CL measures are shown in Table 7-4.

Table 7-4: Correlations between thinking style and CL measures.

Correlated parameters	ρ^*
Thinking style – Fixation duration	-0.033
Thinking style – Fixation count	0.272
Thinking style – NASA-TLX	-0.123

A two sample t-test was performed to the impact of system type on CL, system usability, and bias-related error count. The CL was assessed using three measures, fixation duration, fixation count and NASA-TLX score. There was not a significant difference in fixation duration between TAS (M = 243.5, SD = 82.9) and CAS (M = 250.4, SD = 81.9); t (df) = 2.18, p = 0.8).

There was not a significant difference in fixation count between TAS (M = 1.12, SD = 0.33) and CAS (M = 1.14, SD = 0.59); t (df) = 2.18, p = 0.92). However, there was a significant difference in NASA-TLX score between TAS (M = 29.61, SD = 17.92) and CAS (M = 16.79, SD = 7.65); t (df) = 2.18, p = 0.032).

The t-test revealed that there was not a significant difference in PSSUQ score between TAS (M = 1.93, SD = 1.13) and CAS (M = 1.44, SD = 0.35); t (df) = 2.18, p = 0.19).

For the bias-related error count, the t-test showed that there was a significant difference in bias-related error count between TAS (M = 9.8, SD = 8) and CAS (M = 1.61, SD = 1.8); t (df) = 2.18, p = 0.0012). The results of hypothesis testing for experimental parameters are summarized in Table 7-5.

Table 7-5: Correlations and t-test results. Paired parameters and the corresponding Pearson's correlation coefficient (ρ), P-value, and hypothesis test results for the mean µ.

Parameters	ρ	P-value	Hypothesis test result for µ**
System type – Fixation duration	0.277	0.81	Fail to reject the null hypothesis (µ1 = µ2).
System type – Fixation count	-0.144	0.92	Fail to reject the null hypothesis (µ1 = µ3).
System type – NASATLX	-0.144	0.03	Reject the null hypothesis (µ1 ≠ µ4).
System type – PSSUQ	-0.235	0.19	Fail to reject the null hypothesis (µ1 = µ5).
System type – bias error count**	0.610	0.00	Reject the null hypothesis (µ1 ≠ µ6).

CHAPTER 8

EXPERIMENT 2 DISCUSSION

The results showed that 42% of the subjects possessed an intuitive thinking style, while 58% possessed a deliberate thinking style. Subjects who used the TAS, scored an average of 3.46 in the CRT. Subjects who used the CAS scored an average of 3.92 (11% higher). This score showed that thinking style was approximately equally distributed (intuitive/deliberate) among both groups.

CL was measured by eye-tracking data. Each experimental task is represented by the areas of interest. The annotation of areas of interest depends on the type of task the assembler performed. Subjects with the CAS had a 3% higher fixation duration and 2% higher fixation count when compared to the traditional assistance system. Although the CAS caused higher CL the differences are minimal. This slight difference in CL can be explained by the features and clues added to the cognitive assistance system to help reduce defective products and reworks. In addition, the slightly higher fixation rates may be attributed to the CAS reducing the CL for the participants to focus on what currently requires their attention rather than their attention being diverted to less important information.

Even with added features to the CAS interface, the assemblers could process the instructed tasks on the system interface with a similar average fixation duration as the TAS group. This result showed the effectiveness of the CAS interface in allowing the participants to take in additional information more efficiently. Fixation count measure was normalized to analyze CL for assemblers (Figure 7-5). The analysis showed that the CAS subjects had a 17% higher fixation duration than the TAS. For the system interface, average fixation count was increased by 15% for users of the CAS (Figure 7-6). The increase in fixation duration and fixation count can be explained by the dynamic features within the system that could lead to higher fixation duration and fixation count without it being attributed to CL (e.g. video instructions).

Hart and Staveland's NASA Task Load Index (TLX) (Appendix L) test was used in this experiment to measure the CL resulting from the four tasks. While Experiment 1 was a stand-alone experiment with no comparisons conducted, Experiment 2 compared the CAS to the TAS, which called for another measure for CL. NASA-TLX test was chosen to support the other CL objective measures and to align the results from the eye-tracking with the subjects' NASA-TLX self-reported feedback.

Using the CAS reduced the CL measured by NASA-TLX by 43% when compared to the TAS (Figure 7-7). This decrease indicated a reduction in task complexity effect on users. Results showed that users of the CAS and TAS reported an average NASA-TLX score of 16.8 and 29.9, respectively. The highest task complexity reported for TAS users for the Effort subcategory for an average score of 43. However, the highest task complexity reported for the CAS users for the Performance and Effort subcategories for an average of 19 on NASA-TLX 100 point scale. This shows that using TAS resulted in a much higher perceived effort of use, while CAS increased overall perceived performance.

Errors were defined as a measure of the impact of cognitive bias, with the CAS system group showing a marked improvement in this area. The total cognitive bias-related error count is 85% less for subjects used CAS compared to subjects used TAS. The bias-related error count for the avoidance of information alone increased by 88% when using TAS compared to CAS. On the other hand, using TAS increased the overconfidence bias-related error by 55%.

Error contribution percent is observed solely for each type of bias-related error for both cognitive biases (Figure 7-12 and Figure 7-14). The CAS had on screen clues to resolve the avoidance of information bias-related errors. These clues include video, bold text, and arrows. TAS had the instructions and a picture. As a result, using TAS contributed to a 100% of the errors in that task, with either wrong 3D model design or not using the safety tool to pick up the printed part.

This is the whole point of using an assistance system, to have more clues that helps to not avoid the instructed information such as 3D model modification required.

Using the traditional assistance system contributed to over 90% of assemblers ignoring a step or producing a defective final product. In the automated hybrid assembly mass production, using TAS contributed to over 80% of wrong coding to automate the robot and unnecessary repetition when the robot failed to feed parts in the designated area. In the same task, using TAS contributed to over 70% of ignoring to scrap parts when the task required to. Finally, the CAS had a video while TAS had only picture instructions, therefore, using the TAS contributed to 100% of recording pass for a failure when inspecting parts error occurrence and over 55% wrong parts inspection techniques.

Figures from (Figure 7-15 to Figure 7-18) show the summary of PSSUQ scores. Usability of both systems interfaces was assessed using the PSSUQ scores. The scores are ranked inversely, with 1 being the best performance and 7 being the worst. The

PSSUQ results show that the overall user satisfaction measured by the OVERALL user satisfaction is improved by 25% when using the cognitive assistance system's interface compared to the traditional system interface. For the other subcategories, system usability (SYSUSE) is improved by 21% when using CAS versus TAS. The information quality (INFOQUAL) score is improved by 30%, and the interface quality (INTERQUAL) score is improved by 16%. The PSSUQ results reveal that users of CAS are more satisfied with the system's performance and interface when compared to TAS.

Subjects' answers in the comments section of the PSSUQ questionnaire were collected summarized in Table 8-1. The users' feedback is used for continuous improvement and to resolve issues reported by users of both systems. This feedback can produce an improved future version of the system, resolve issues within the system and help to modify the system to help in other A5.0 tasks.

Table 8-1: Subjects' in TAS and CAS groups comments in the PSSUQ comment sections.

TAS Group	CAS Group
• The system worked great to accomplish tasks. • Interface was easy to read/ understand. • All information was obvious and provided. • The system did not play a large role in how easy/quick it was to recover. • Straightforward tasks. • Pictures pose is confusing. • No error feedback. • Unique type of mouse.	• Intuitive. • Videos helped when stuck. • Was clear shown on screen. • I was very comfortable after spending one minute with the system. • The colors were mixed which confused me only in the slightest. • Easy to understand quickly. • A second monitor would be helpful. • Screen swapping slowed pace. • Hard to understand where to place the robot. • Instructions should be split screen with the coding instead of flipping back and forth. • No error message received. • Very simple.

Correlation analysis showed that thinking style measured by CRT was not highly related to CL measures (fixation duration, fixation count, and NASA-TLX). The fixation duration slightly decreases when the human has a deliberate thinking style ($\rho = -0.033$). Fixation count increases with the increase of CRT score ($\rho = 0.272$), however, this increase isn't major. This behavior can be explained by the tendency to focus on the task rather than spending longer periods of fixations with a lower fixation count (hence the deliberate thinking style). The opposite is true for the intuitive-thinking assemblers.

Subjects with higher CRT reported less task complexity in NASA-TLX test, which can be explained by the deliberate thinking style that helps in simplifying task requirements. Although the CAS caused assemblers to spend more fixation time and count on required tasks, the difference for that parameter is insignificant, so the CL increase was not affecting assemblers negatively.

CHAPTER 9

CONCLUSIONS

Manufacturing assembly is combining previously made components or subassemblies into a final finished product. Human judgement importance is continuously increasing in Industry 5.0. Interests in Industry 4.0 focus on opportunities that can benefit industry by including new digital technologies [3] and by new frameworks that are developed to test the effects of applying such technologies [5]. The fifth industrial revolution includes improved concepts compared to 4.0 such as mass personalization, enhanced customer satisfaction, utilization of the unique human judgement, enhanced quality tools, enhanced usage of skilled jobs, sustainability, Cobots connected with human workers, and more accurate decision support models. In assembly, cognitive performance is the degree to which individual workers can understand and process relevant signals from the assembly situation; and finally, make decisions that lead to actions that perform correct component assembly.

The adoption of the I5.0 settings introduces the concept of worker 5.0 and imposes the following challenges on operators in assembly lines:

1. The demand for technology and the use of complex procedures enforce more pressure on operators.

2. Mass customization of products creates challenges for workers to confront the exchange between automated systems that are highly productive and manual systems that are more flexible.

3. The higher expectations of human to have more work accuracy and collaboration with all work elements.

These challenges were the motivation for the work in this study. The primary objective of this study is to focus on cognitive aspects and to design better workplaces for the people in assembly 5.0.

Mark et al. established a three-layer model to implement Industry 4.0/5.0 concepts in small- and medium-sized enterprises (SMEs) [1]. These three layers are the design level, the implementation level, and the operational level. The research framework of this dissertation designed according to the aforementioned three-layer model to emphasize the steps and goals of the dissertation.

The first step of the framework included understanding the manufacturing assembly process by conducting Experiment 1 to investigate the applicability of eye-tracking technology in assembly. During step 1, we specified the process variables that we need to assess in Assembly 5.0. Also, we collected information about work conditions we need to set up for Assembly 5.0 in the lab. Finally, we introduced the cognitive assistance system's technical features.

In the second step of the framework, we prepared the work environment for the Assembly 5.0 experiment. We chose the TAS from LEGO ® and modified it to suit the goals of the work. Finally, we designed the CAS based on results and outcomes revealed from Experiment 1 in the first step. The system features were applied, and the system was ready to be used by participants.

In the third and final step, we conducted Experiment 2 to evaluate the CAS compared to TAS in I5.0 settings. We investigated the effect of using CAS on workers' CL and cognitive bias-related human performance. We investigated the effect of human thinking style on CL using the dual-system theory.

To achieve the research objective of this study, we followed an experimental method that comprised two experiments, Experiment 1 and Experiment 2. Experiment 1 included a step-by-step instructed manual assembly task. Eye-tracking technology was as an objective measure for assemblers' CL. Choosing eye-tracking areas of interest plays an important role in specifying CL for each task accurately. The empirical results of the first experiment revealed that CL can successfully be measured using eye-tracking variables in assembly tasks. Higher fixation duration and fixation count showed an increase in CL during the corresponding assembly job. The increase in transitions between areas of interest for given tasks and the error count show a decrease in human performance. Based on the evaluation of cognitive bias existence during Experiment 1 assembly tasks, four cognitive biases were found to affect the human performance in assembly: overconfidence, avoidance of information, availability bias, and the memory bias. It was found that availability and avoidance of information biases occur in the information acquisition stage of assembly work. Overconfidence and memory biases occur in the information processing stage. Overconfidence and avoidance of information were chosen for further investigation in Experiment 2. The results from Experiment 1 were used as guidelines for designing Experiment 2.

It is useful to summarize the experimental methods that were used in Experiment 2. The experiment focused on assessing CL in A5.0 work environment. The first step was choosing the workplace elements to comprise I5.0 fundamental concepts. Such elements include the ergonomic laboratory features, human performance monitoring, additive manufacturing, hybrid assembly, increased work complexity, and the usage of eye-tracking. The TAS and CAS systems were used in Experiment 2 as information delivery methods. The TAS was modified from LEGO® to serve as a comparison rival. CAS reduced CL, improve human performance, and mitigate cognitive biases in A5.0 work features. Experiment 2 included four designed assembly tasks, accompanied by four inspection tasks.

Based on Experiment 2 results, the fixation duration decreases when the human has a deliberate thinking style while the fixation count increases. This behavior can be explained by the tendency to focus on the task rather than spending longer periods of fixations with less fixation count (hence the deliberate thinking style). The opposite is true for the intuitive-thinking assemblers. This result applies to assemblers regardless of the assistance system they used.

Although using the CAS caused higher CL, the differences are minimal. This slight difference in CL can be explained by the features and clues added to the CAS to help reduce defective products and reworks.

In manufacturing assembly, cognitive biases are the chief contribution to assembly errors and mitigating them can help in improving human performance in A5.0. In this study, using CAS could successfully mitigate bias-related errors and improve work efficiency.

The users' feedback is used for continuous improvement and to resolve issues reported by users. This feedback can produce an improved future version of the system, resolve issues within the system, and modify the system to be used for other experiment.

CHAPTER 10

RESEARCH GAP AND CONTIRBUTION

Because of the higher complexity and work demand in the I5.0 work environment, CAS was introduced to workers in the I5.0 to improve performance, reduce the impact of CL, and reduce the effect of cognitive biases. A research gap was found in integrating I5.0 topics into assembly operations. To fill this gap, this study addresses integration of the following I5.0 elements into the assembly environment to improve work and efficiency:

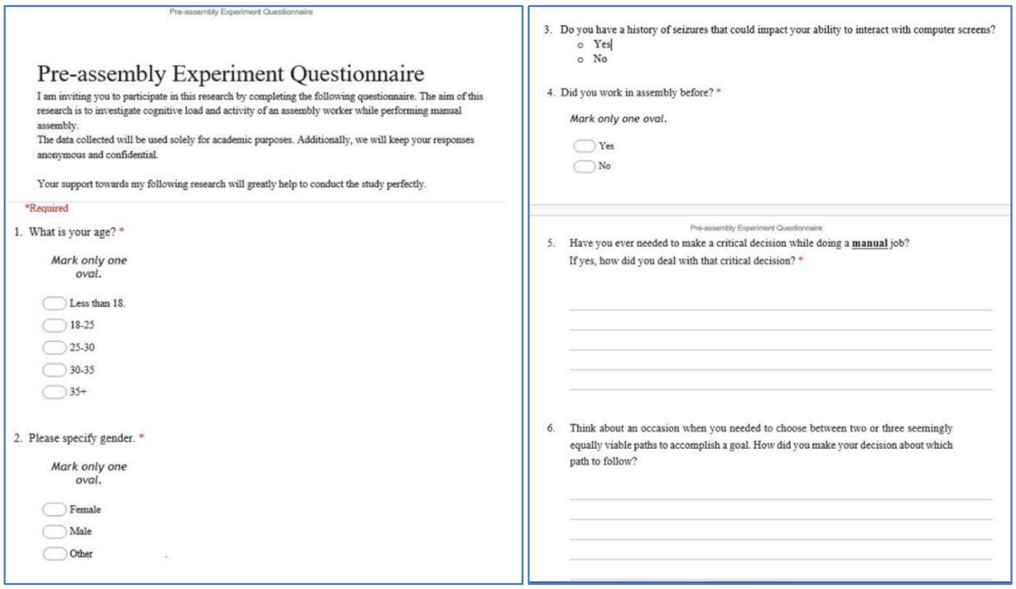
1) Industry 5.0 work standards, concepts, and requirements, 2) Ergonomic work standards, 3) Additive manufacturing, 4) Eye-tracking and eye movement analysis, 5) Dual systems theory (intuitive/deliberate) and cognitive heuristics and biases, 6) Cognitive assistance and related practical solutions (introduction of the CAS to support I5.0 assembly workers), and 7) User satisfaction and continuous improvement.

This study expands the use of cognitive ergonomic tools in the mass customization assembly environment, especially eye-tracking, to employ it for workers in assembly 5.0 benefits. This goal was reached by the minimal increase in CL measured by eye-tracking, reduction of CL reported by assemblers through NASA-TLX, and mitigating cognitive biases to reduce bias-related errors in A5.0.

The users' feedback is used for continuous improvement and to resolve issues reported by users. This feedback can produce an improved future version of the system, resolve issues within the system, and modify the system to be used for other experiment

APPENDIX A

PRE-EXPERIMENT QUESTIONNAIRE (EXPERIMENT 1)



Pre-assembly Experiment Questionnaire

Pre-assembly Experiment Questionnaire

I am inviting you to participate in this research by completing the following questionnaire. The aim of this research is to investigate cognitive load and activity of an assembly worker while performing manual assembly.
The data collected will be used solely for academic purposes. Additionally, we will keep your responses anonymous and confidential.

Your support towards my following research will greatly help to conduct the study perfectly.

*Required

1. What is your age? *

   Mark only one oval.

   - Less than 18.
   - 18-25
   - 25-30
   - 30-35
   - 35+

2. Please specify gender. *

   Mark only one oval.

   - Female
   - Male
   - Other

3. Do you have a history of seizures that could impact your ability to interact with computer screens?
   - Yes
   - No

4. Did you work in assembly before? *

   Mark only one oval.

   - Yes
   - No

Pre-assembly Experiment Questionnaire

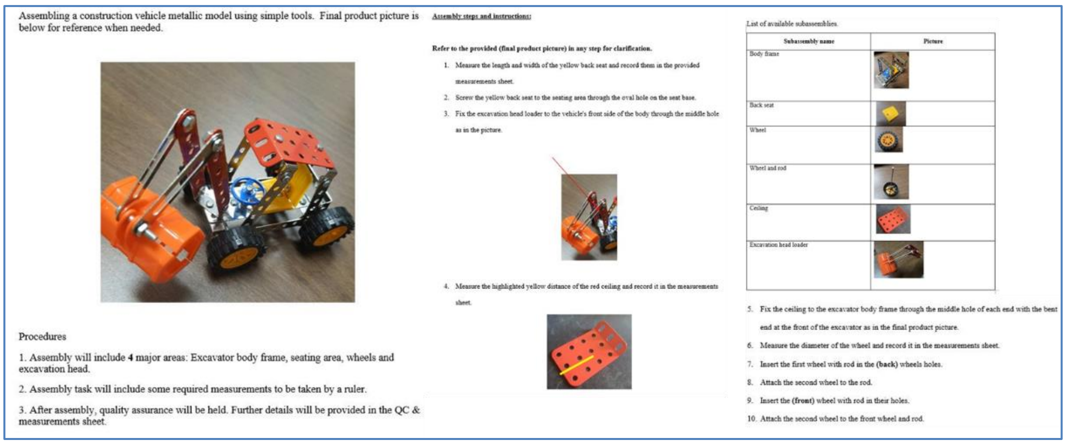
5. Have you ever needed to make a critical decision while doing a **manual** job?
   If yes, how did you deal with that critical decision? *

6. Think about an occasion when you needed to choose between two or three seemingly equally viable paths to accomplish a goal. How did you make your decision about which path to follow?

Figure A-1: Pre-experiment questionnaire (Experiment 1).

APPENDIX B

EXPRIMENT 1 ASSEMBLY INSTRUCTIONS



Assembling a construction vehicle metallic model using simple tools. Final product picture is below for reference when needed.

Procedures

1. Assembly will include **4** major areas: Excavator body frame, seating area, wheels and excavation head.

2. Assembly task will include some required measurements to be taken by a ruler.

3. After assembly, quality assurance will be held. Further details will be provided in the QC & measurements sheet.

Assembly steps and instructions:

Refer to the provided (final product picture) in any step for clarification.

1. Measure the length and width of the yellow back seat and record them in the provided measurements sheet.
2. Screw the yellow back seat to the seating area through the oval hole on the seat base.
3. Fix the excavation head loader to the vehicle's front side of the body through the middle hole as in the picture.
4. Measure the highlighted yellow distance of the red ceiling and record it in the measurements sheet.

List of available subassemblies.

Subassembly name	Picture
Body frame	
Back seat	
Wheel	
Wheel and rod	
Ceiling	
Excavation head loader	

5. Fix the ceiling to the excavator body frame through the middle hole of each end with the bent end at the front of the excavator as in the final product picture.
6. Measure the diameter of the wheel and record it in the measurements sheet.
7. Insert the first wheel with rod in the **(back)** wheels holes.
8. Attach the second wheel to the rod.
9. Insert the **(front)** wheel with rod in their holes.
10. Attach the second wheel to the front wheel and rod.

Figure B-2: Experiment 1 assembly instructions.

APPENDIX C

QUALITY CONTROL AND MEASUREMENT SHEET (EXPERIMENT 1)

Participant Number:

Part name	Recorded measurement at assembly (inch)
Back Seat Length	
Back seat width	
Ceiling highlighted distance	
Wheel diameter	

- **Quality assurance and control:**

Check ✓ the box beside the quality assurance step that you have done correctly. If there is a quality issue, X the box and comment beside it what is wrong.

1. Back seat is sturdy and does not wiggle. ☐

2. The excavation head loader moves around freely in 180° and the screw is not loose. ☐

3. The ceiling bent edge is facing the front of the excavator above the steering wheel. ☐

4. Wheels are fixed in place and not going out of the rod. ☐

Figure C-3: Quality control and measurement sheet (Experiment 1).

APPENDIX D

TRANSITION MATRICES

From \ To	Assembly Sheet	Finished Product Picture	Fix Backseat	Fix Loader Head	Fix Wheels	Fix the Ceiling	Measure Backseat L & W	Measure Ceiling Highlighted Distance	Measure Wheel Diameter
Assembly Sheet	NA	18	17	29	24	12	19	27	7
Finished Product Picture	4	NA	4	4	14	27	0	0	0
Fix Backseat	19	2	NA	0	0	0	0	0	0
Fix Loader Head	1	3	0	NA	0	0	0	1	0
Fix Wheels	20	15	0	1	NA	0	0	0	0
Fix the Ceiling	19	14	0	0	0	NA	0	0	1
Measure Backseat L & W	15	0	0	0	0	0	NA	0	0
Measure Ceiling Highlighted Distance	25	0	0	1	0	0	0	NA	1
Measure Wheel Diameter	6	0	0	0	1	0	0	0	NA

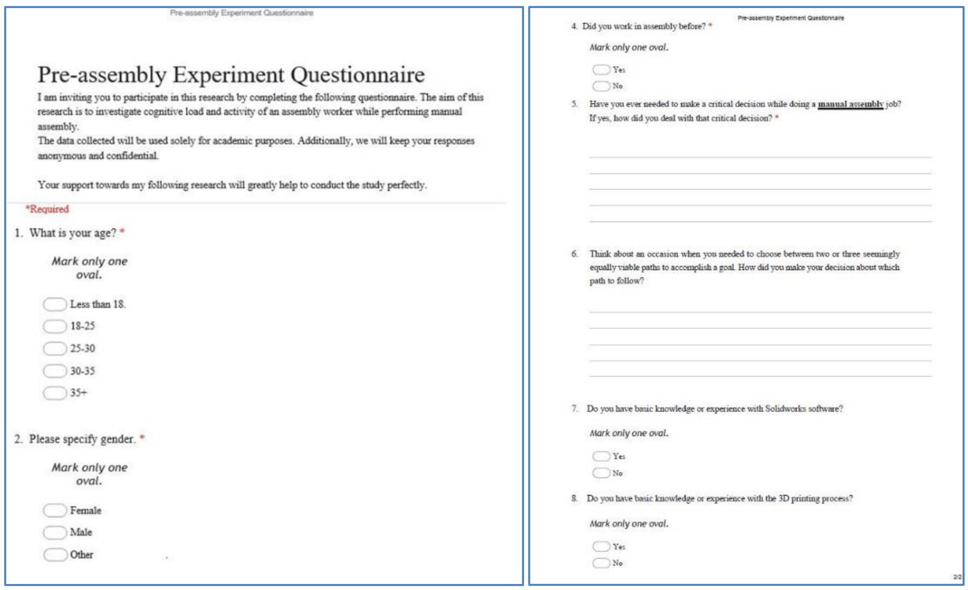
Figure D-4: Experiment 1 transition matrix for the assembly phase (generated by iMotions).

transitions summary												
All respondents during inspection												
From \ To	Assembly Sheet	Attach Backseat	Attach Loader head	Attach Ceiling	Attach wheels	Inspect Backseat	Inspect ceiling	Inspect loader head	Measure wheel diameter	Product picture	Inspect wheels	Measure BS
Inspect BS	0	1	0	0	0	0	1	9	1	1	1	0
Inspect LH	0	0	0	0	0	1	11	0	0	0	0	0
Inspect ceiling	0	0	0	0	0	0	0	0	0	1	11	0
Inspect wheels	0	0	0	0	0	2	1	1	0	0	0	0

Figure D-5: Experiment 1 transition matrix for the inspection phase (generated by iMotions).

APPENDIX E

PRE-EXPERIMENT QUESTIONNAIRE (EXPERIMENT 2)



Pre-assembly Experiment Questionnaire

Pre-assembly Experiment Questionnaire

I am inviting you to participate in this research by completing the following questionnaire. The aim of this research is to investigate cognitive load and activity of an assembly worker while performing manual assembly.
The data collected will be used solely for academic purposes. Additionally, we will keep your responses anonymous and confidential.

Your support towards my following research will greatly help to conduct the study perfectly.

*Required

1. What is your age? *

Mark only one oval.

- Less than 18.
- 18-25
- 25-30
- 30-35
- 35+

2. Please specify gender. *

Mark only one oval.

- Female
- Male
- Other

Pre-assembly Experiment Questionnaire

4. Did you work in assembly before? *

Mark only one oval.

- Yes
- No

5. Have you ever needed to make a critical decision while doing a **manual assembly** job? If yes, how did you deal with that critical decision? *

6. Think about an occasion when you needed to choose between two or three seemingly equally visible paths to accomplish a goal. How did you make your decision about which path to follow?

7. Do you have basic knowledge or experience with Solidworks software?

Mark only one oval.

- Yes
- No

8. Do you have basic knowledge or experience with the 3D printing process?

Mark only one oval.

- Yes
- No

Figure E-6: Experiment 1 transition matrix for the inspection phase (generated by iMotions).

APPENDIX F

POWER ANALYSIS (EXPERIMENT 2)

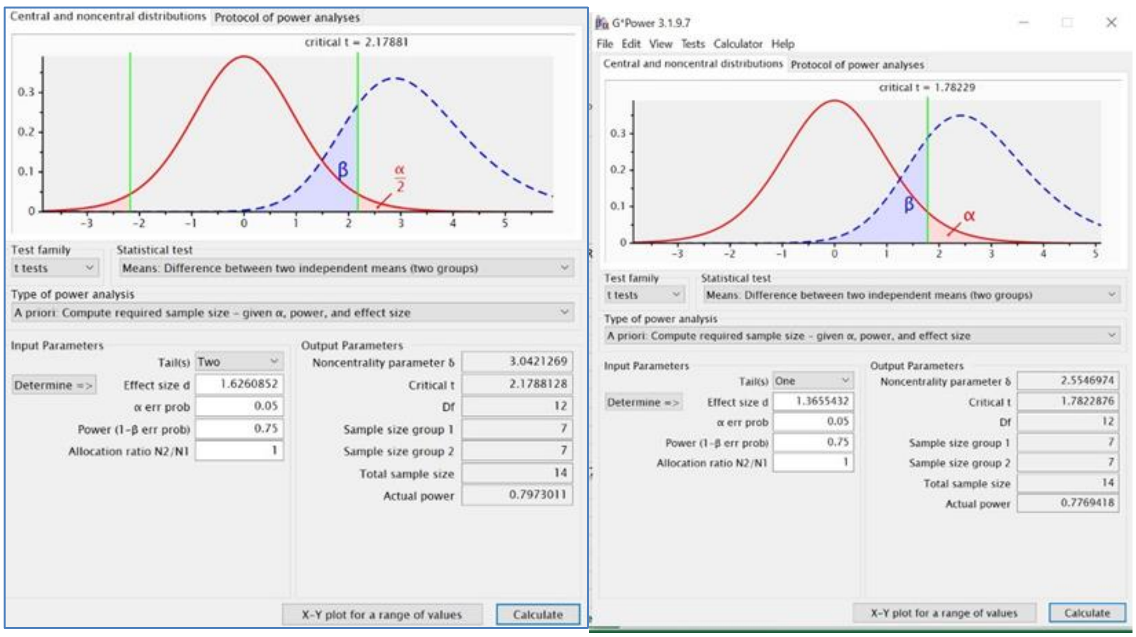


Figure F-7: Power analysis β=0.75 based on hardest task duration (left) and fixation duration (right).

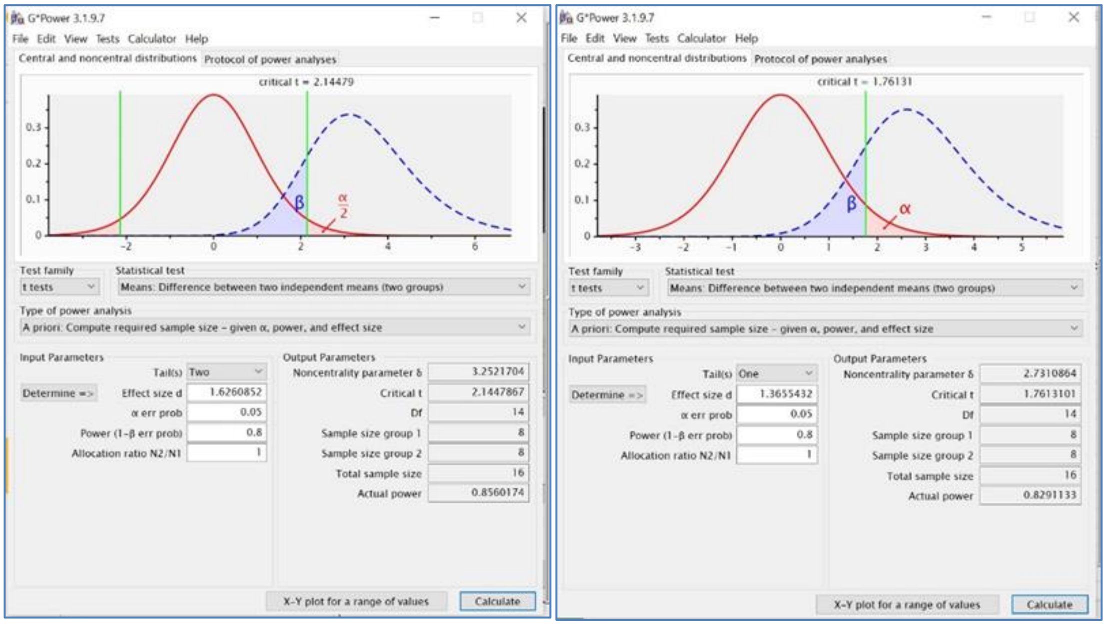


Figure F-8: Power analysis β=0.8 based on hardest task duration (left) and fixation duration (right).

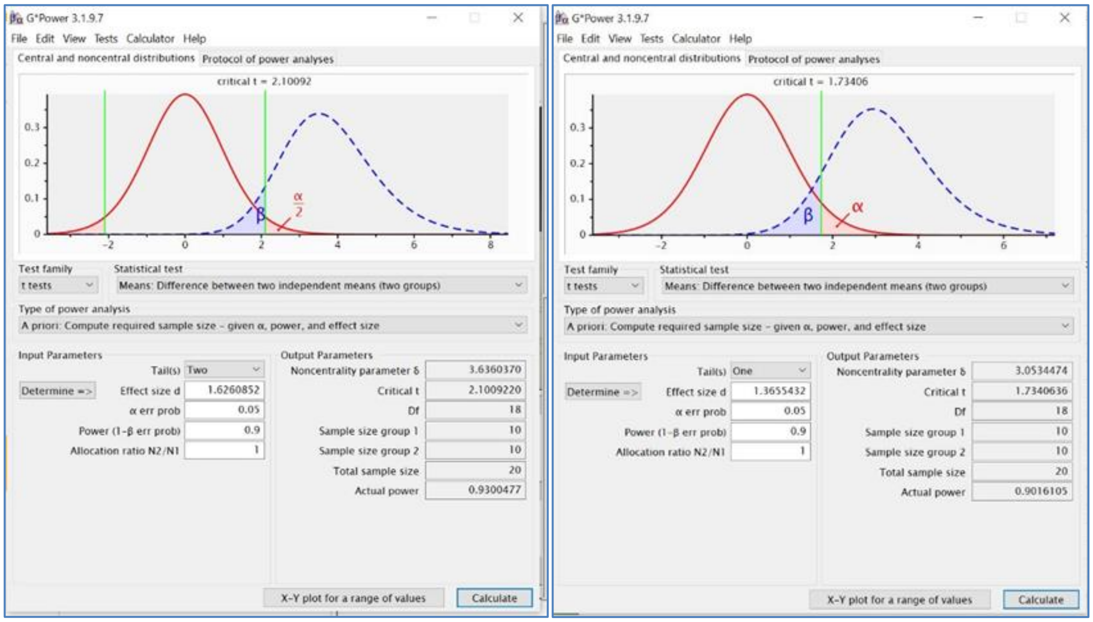


Figure F-9: Power analysis β=0.9 based on hardest task duration (left) and fixation duration (right).

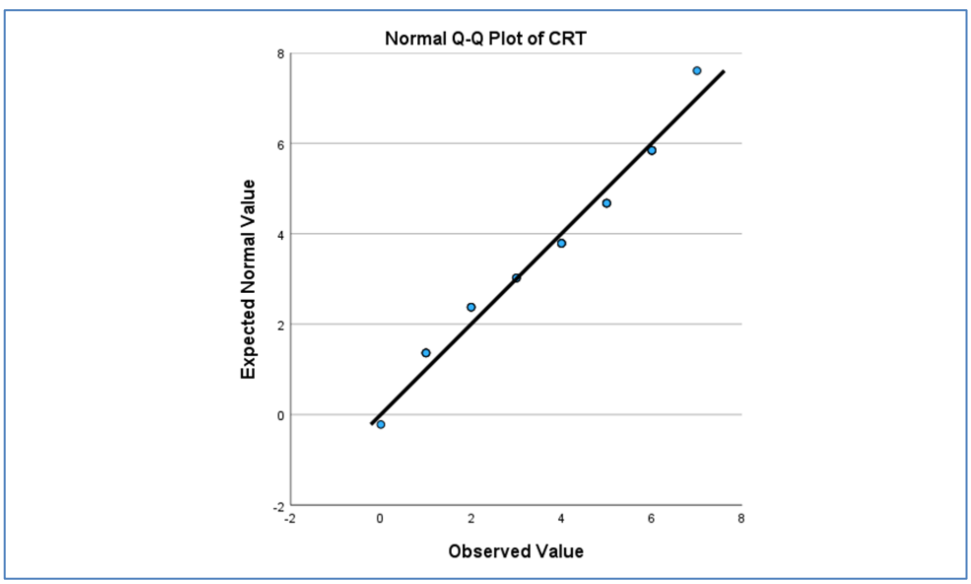


Figure F-10: Normality test for the CRT.

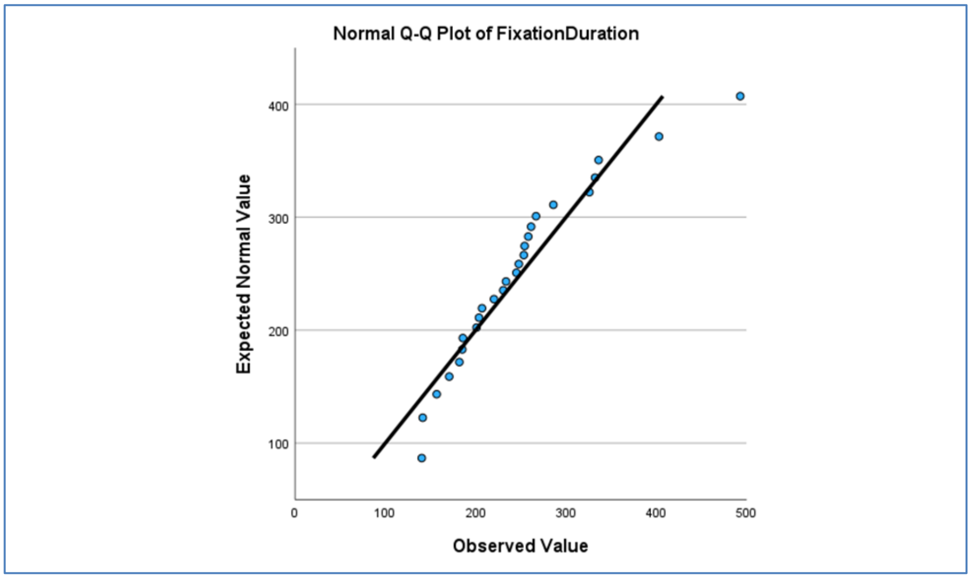


Figure F-11: Normality test for the fixation Duration.

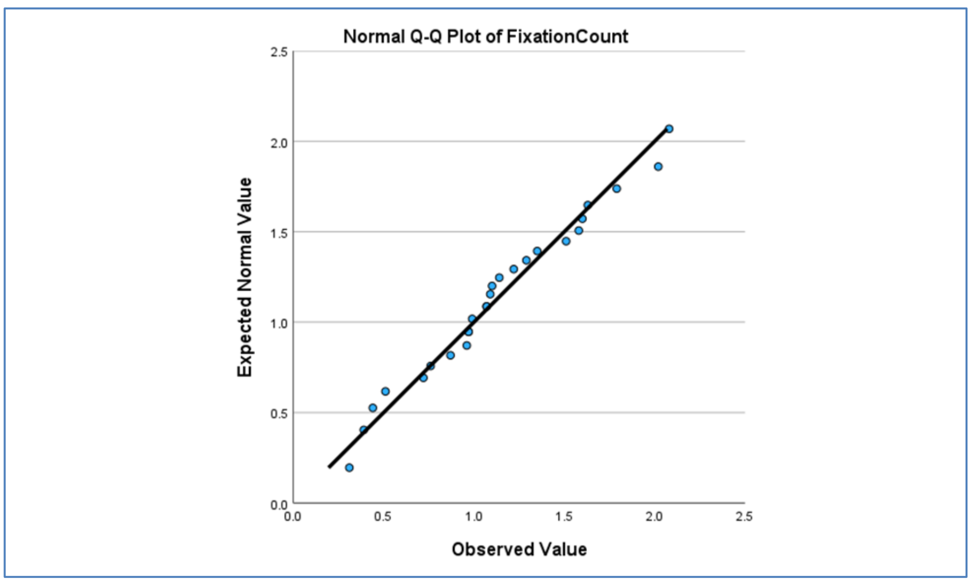


Figure F-12: Normality test for the fixation Count.

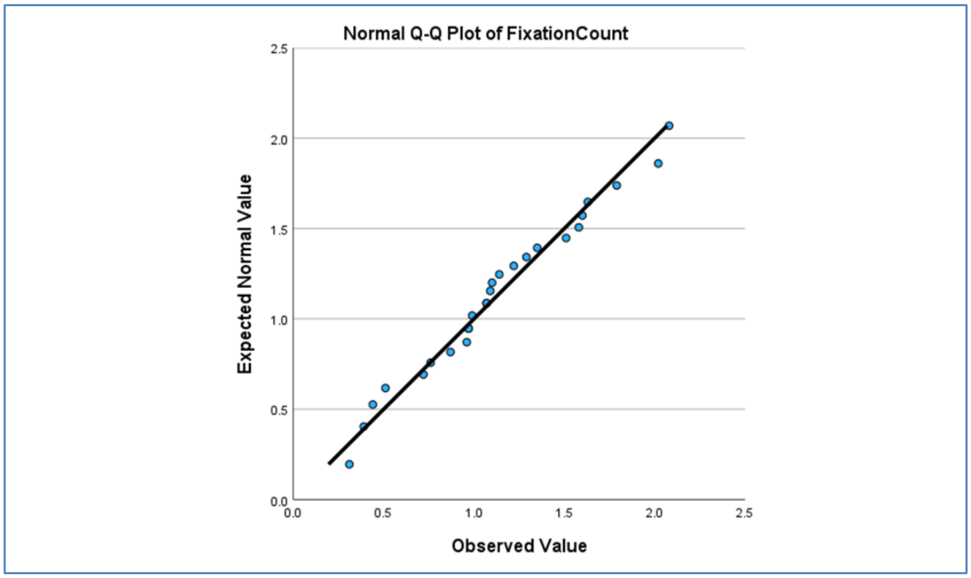


Figure F-13: Normality test for the fixation Count.

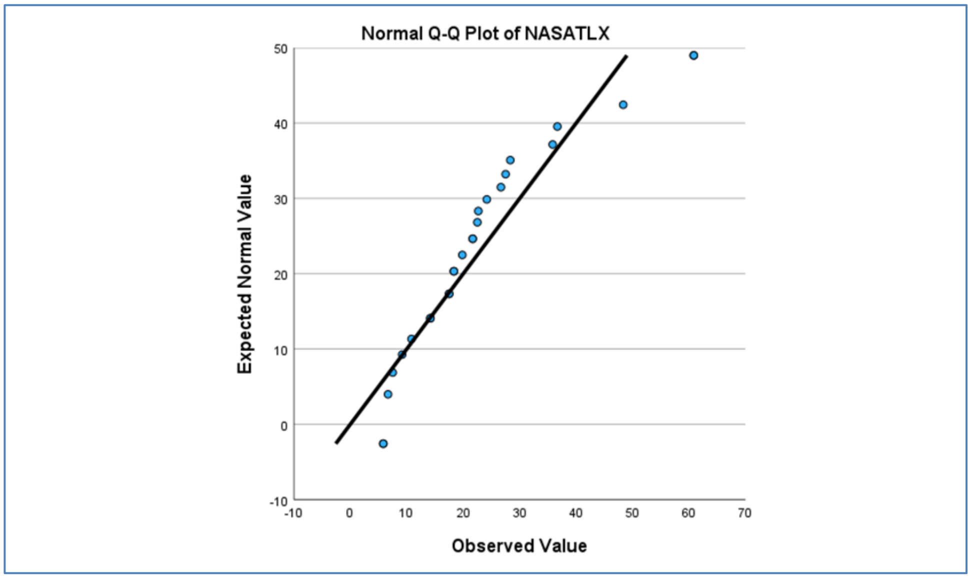


Figure F-14: Normality test for the PSSUQ.

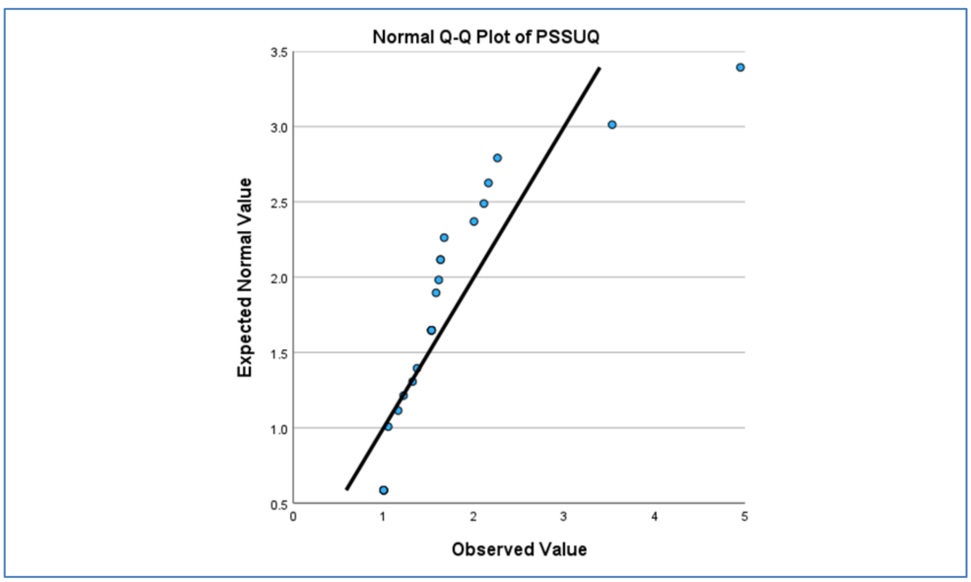


Figure F-15: Normality test for the NASA-TLX.

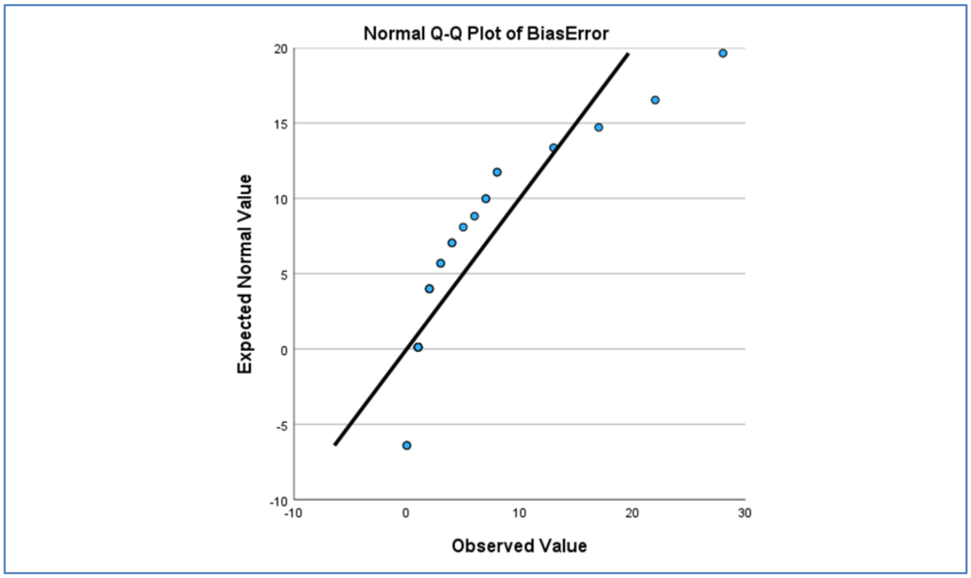


Figure F-16: Normality test for the bias-related error count.

APPENDIX G

THE CRT TEST (EXPERIMENT 2)

- The expanded CRT questionnaire to measure reflective thinking scores.

Answer the questions below.

Copy of the CRT expanded test 7-questions version.

(1) A bat and a ball cost $1.10 in total. The bat costs a dollar more than the ball. How much does the ball cost? ____ cents.

(2) If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets? ____ minutes.

(3) In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake? ____ days.

(4) If John can drink one barrel of water in 6 days, and Mary can drink one barrel of water in 12 days, how long would it take them to drink one barrel of water together? _____ days.

(5) Jerry received both the 15th highest and the 15th lowest mark in the class. How many students are in the class? ______ students.

(6) A man buys a pig for $60, sells it for $70, buys it back for $80, and sells it finally for $90. How much has he made? _____ dollars.

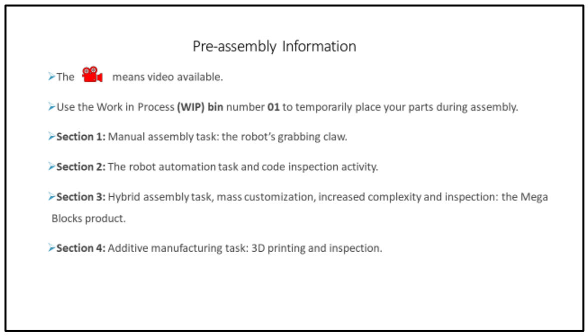
(7) Simon decided to invest $8,000 in the stock market one day early in

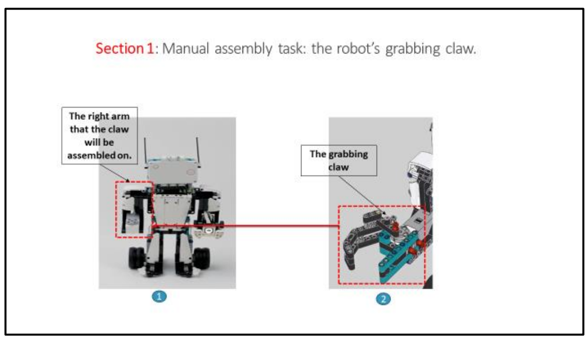
2008. Six months after he invested, on July 17, the stocks he had purchased were down 50%. Fortunately for Simon, from July 17 to October 17, the stocks he had purchased went up 75%. At this point, Simon has:

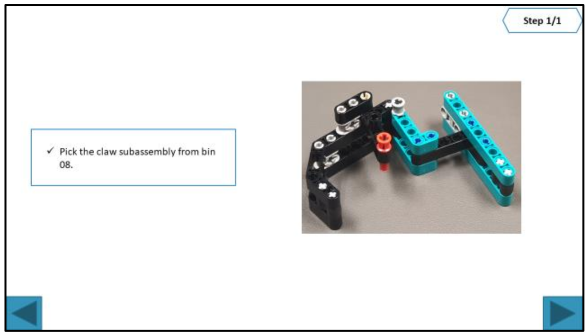
a. broken even in the stock market, b. is ahead of where he began, c. has lost money

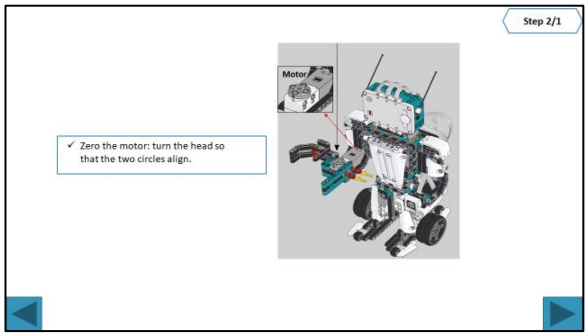
APPENDIX H

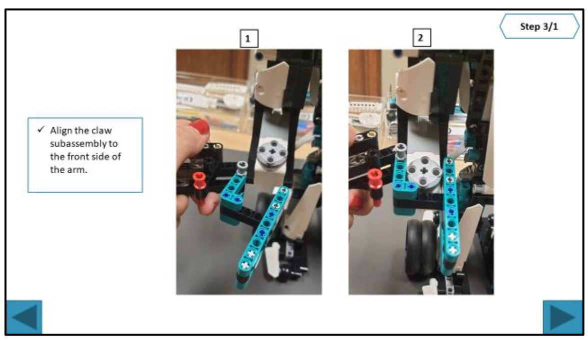
THE TRADITIONAL ASSISTANCE SYSTEM (TAS)

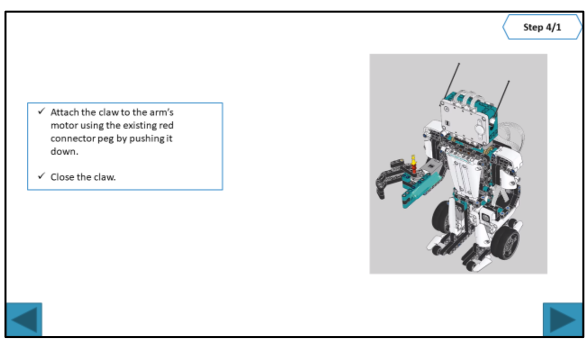


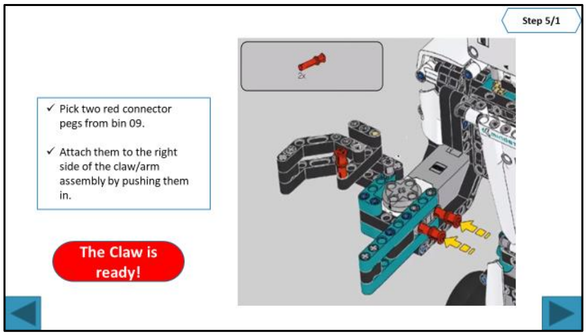



Step 1/1
✓ Pick the claw subassembly from bin 08.

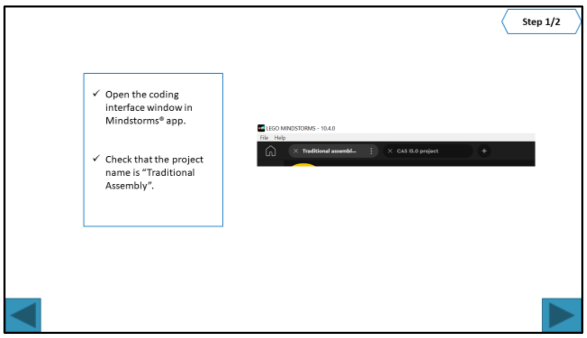

Step 2/1
✓ Zero the motor: turn the head so that the two circles align.
Motor

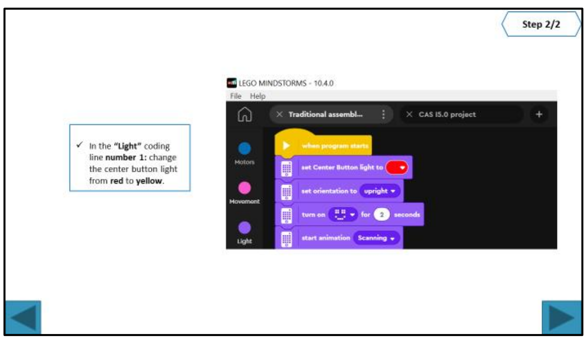

Step 3/1
✓ Align the claw subassembly to the front side of the arm.
1
2

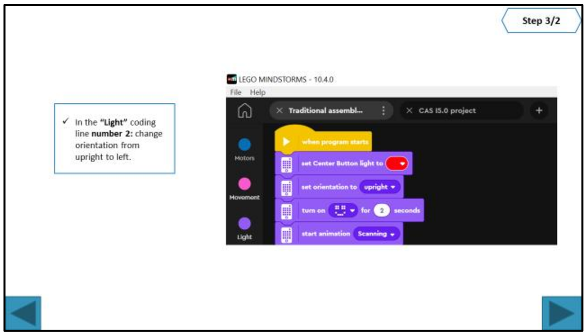

Step 4/1
✓ Attach the claw to the arm's motor using the existing red connector peg by pushing it down.
✓ Close the claw.

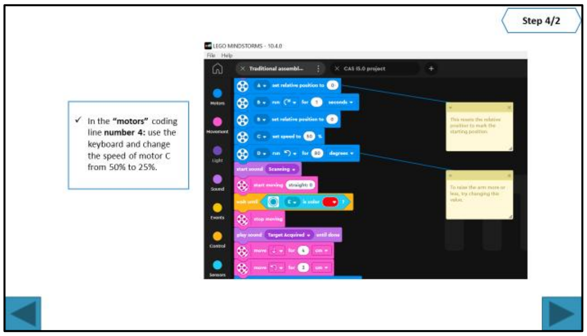

Step 5/1
✓ Pick two red connector pegs from bin 09.
✓ Attach them to the right side of the claw/arm assembly by pushing them in.
The Claw is ready!
2x

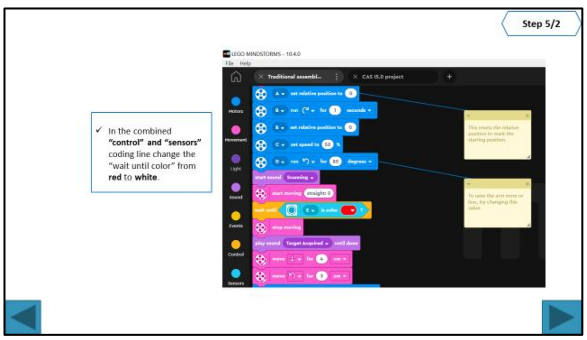

Section 2: The Robot automation task and code testing activity.

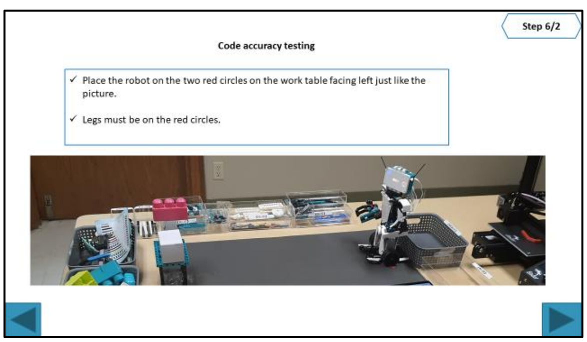

Step 1/2
✓ Open the coding interface window in Mindstorms® app.
✓ Check that the project name is "Traditional Assembly".
LEGO MINDSTORMS - 10.4.0
File Help
Traditional assembl...
CAS I5.0 project

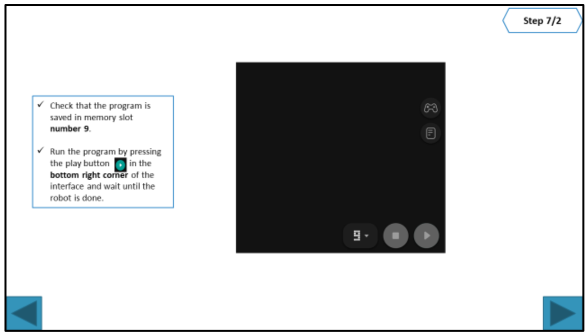

Step 2/2
✓ In the **"Light"** coding line **number 1:** change the center button light from **red** to **yellow**.
LEGO MINDSTORMS - 10.4.0
File Help
Traditional assembl...
CAS I5.0 project
Motors
Movement
Light
when program starts
set Center Button light to
set orientation to upright
turn on for 2 seconds
start animation Scanning

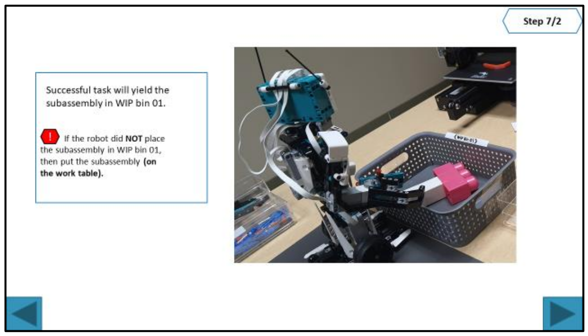

Step 3/2
In the "Light" coding line number 2: change orientation from upright to left.
LEGO MINDSTORMS - 10.4.0
File Help
Traditional assembl...
CAS I5.0 project
Motors
Movement
Light
when program starts
set Center Button light to
set orientation to upright
turn on for 2 seconds
start animation Scanning

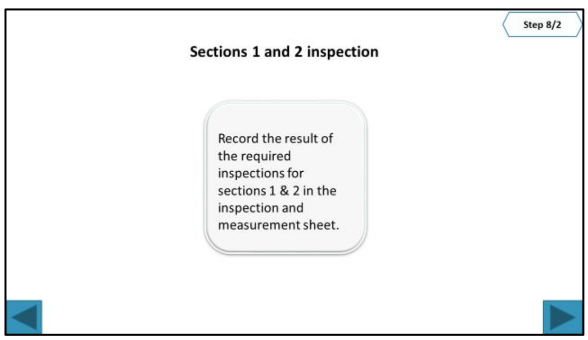

Step 4/2
In the "motors" coding line number 4: use the keyboard and change the speed of motor C from 50% to 25%.
LEGO MINDSTORMS - 10.4.0

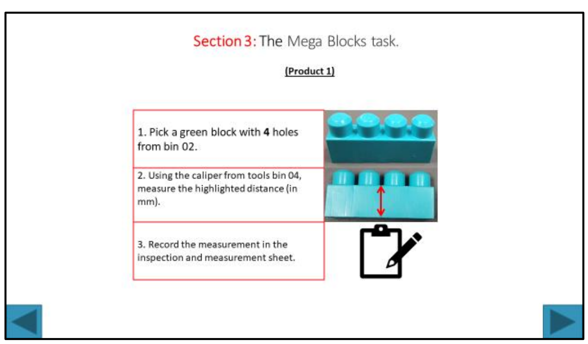

Step 5/2
In the combined "control" and "sensors" coding line change the "wait until color" from red to white.
LEGO MINDSTORMS - 10.4.0


Step 6/2
Code accuracy testing
Place the robot on the two red circles on the work table facing left just like the picture.
Legs must be on the red circles.


Step 7/2
Check that the program is saved in memory slot number 9.
Run the program by pressing the play button in the bottom right corner of the interface and wait until the robot is done.


Step 7/2
Successful task will yield the subassembly in WIP bin 01.
If the robot did NOT place the subassembly in WIP bin 01, then put the subassembly (on the work table).


Step 8/2
Sections 1 and 2 inspection
Record the result of the required inspections for sections 1 & 2 in the inspection and measurement sheet.


Section 3: The Mega Blocks task.
(Product 1)
1. Pick a green block with 4 holes from bin 02.
2. Using the caliper from tools bin 04, measure the highlighted distance (in mm).
3. Record the measurement in the inspection and measurement sheet.

4. Pick a yellow block with 2 holes from bin 02.	
5. Attach the yellow block to the green block on the right side.	
6. Pick the subassembly fed by the robot from WIP bin 01.	

If successful automation

7.a Attach the subassembly fed by the robot to the far left of the existing assembly.

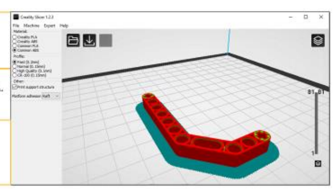
If failed automation

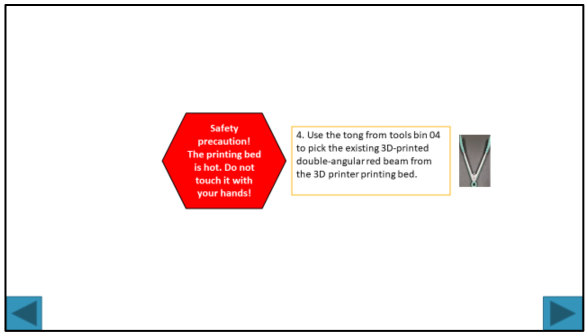
7.b If the robot **failed to** place the subassembly in WIP bin 01, pick the part from the table and place it in the scrap bin 03.

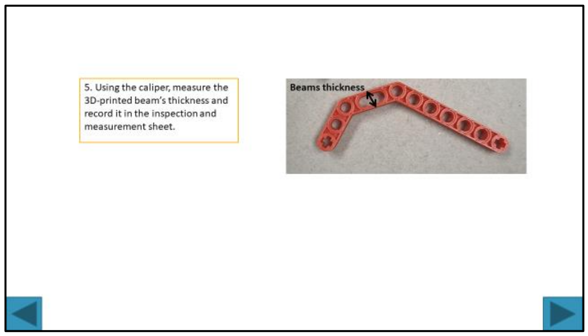
(Product 2)

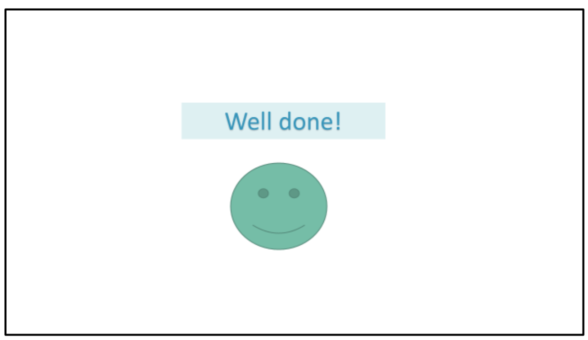
1. Pick a pink block with 4 holes from bin 02.	
2. Pick a yellow block with 1 hole from bin 02 and attach it to the far right.	
3. Pick a green block with 2 holes and attach it to the yellow block only hole with the edge pointing to the left.	

Section 4: The 3D-printing task

1. On the PC screen, go the upper left corner of Creality Slicer software.	
2. Under Material, select the Creality PLA.	
3. Under Profile: select High Quality.	

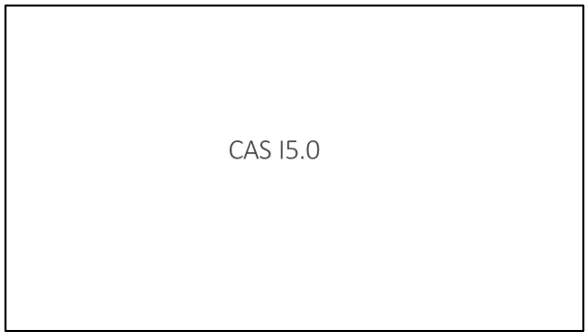

Safety precaution! The printing bed is hot. Do not touch it with your hands!
4. Use the tong from tools bin 04 to pick the existing 3D-printed double-angular red beam from the 3D printer printing bed.

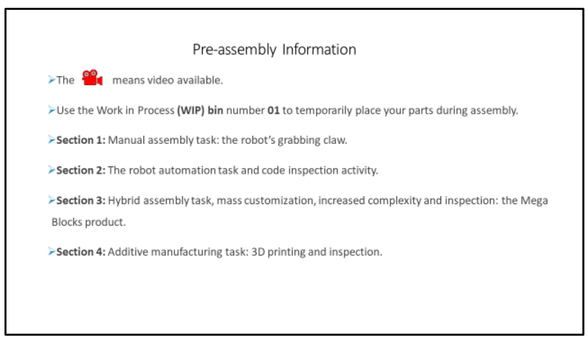

5. Using the caliper, measure the 3D-printed beam's thickness and record it in the inspection and measurement sheet.
Beams thickness

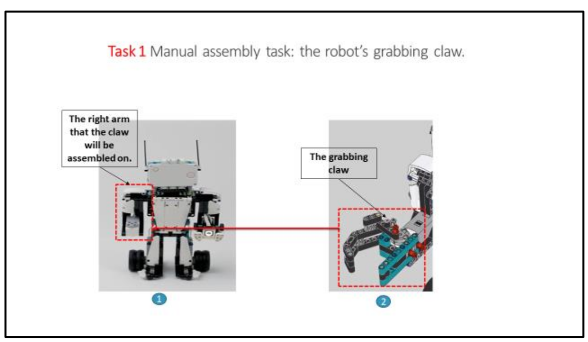

Well done!

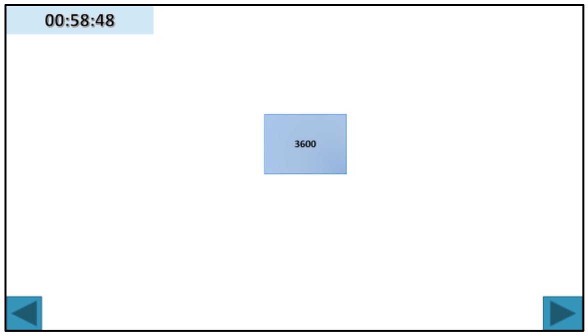
APPENDIX I

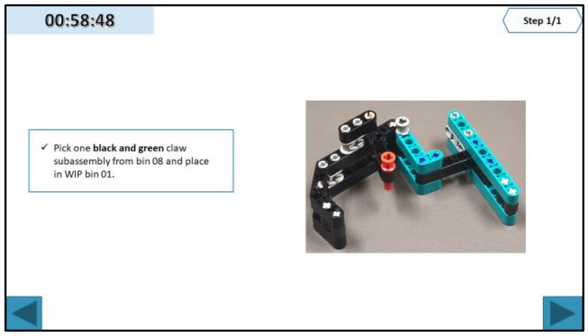
THE COGNITIVE ASSISTANCE SYSTEM (CAS)

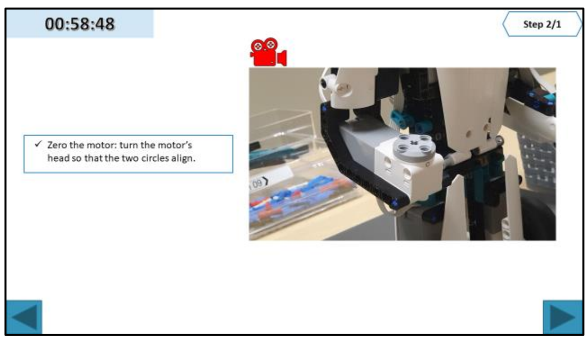


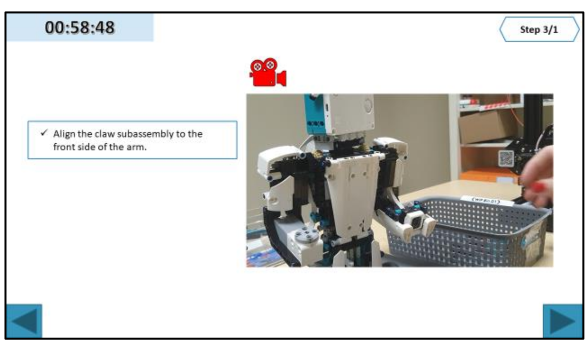


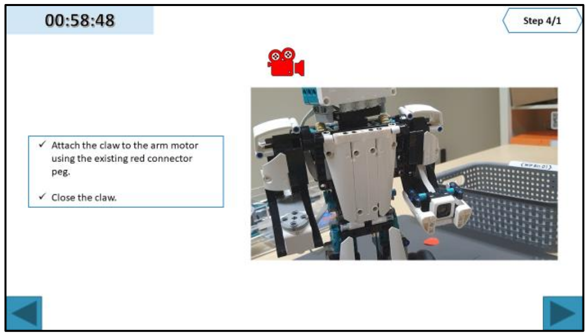


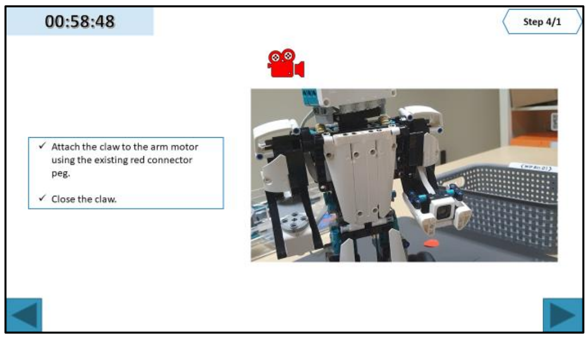

00:58:48
3600

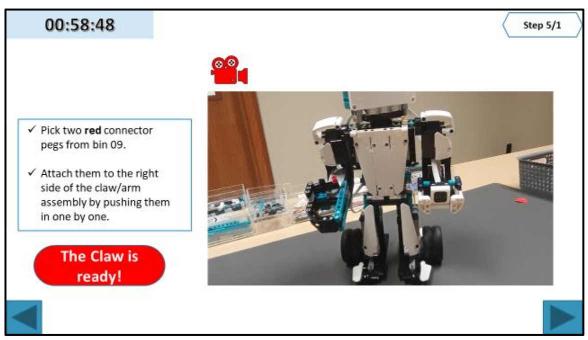

00:58:48
Step 1/1
✓ Pick one **black and green** claw subassembly from bin 08 and place in WIP bin 01.

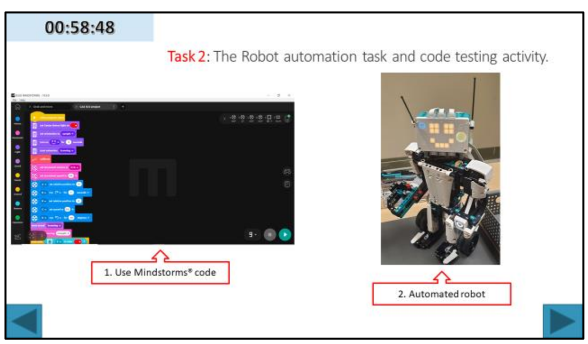

00:58:48
Step 2/1
✓ Zero the motor: turn the motor's head so that the two circles align.

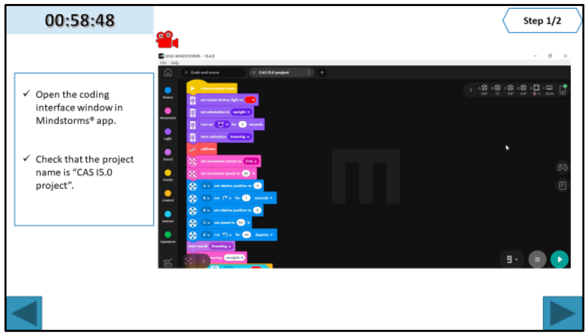

00:58:48
Step 3/1
✓ Align the claw subassembly to the front side of the arm.

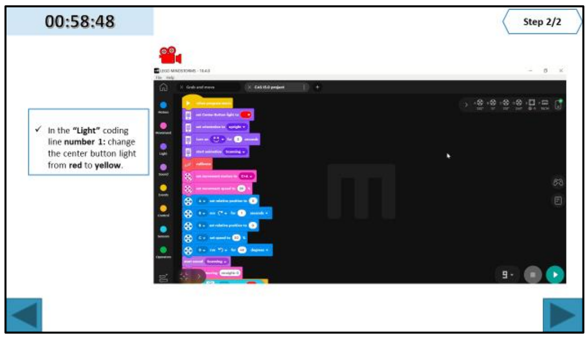

00:58:48
Step 4/1
Attach the claw to the arm motor using the existing red connector peg.
Close the claw.

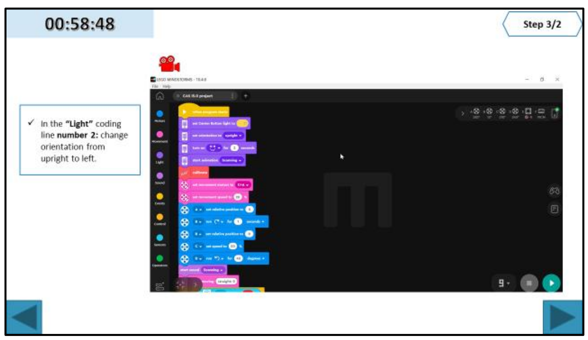

00:58:48
Step 4/1
Attach the claw to the arm motor using the existing red connector peg.
Close the claw.

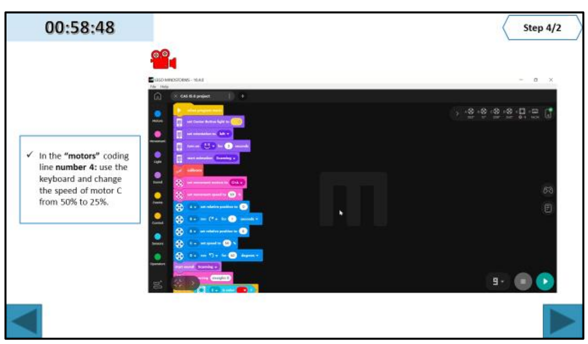

00:58:48
Step 5/1
Pick two red connector pegs from bin 09.
Attach them to the right side of the claw/arm assembly by pushing them in one by one.
The Claw is ready!

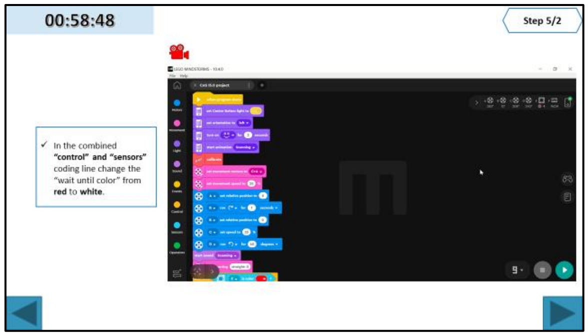

00:58:48
Task 2: The Robot automation task and code testing activity.
1. Use Mindstorms® code
2. Automated robot

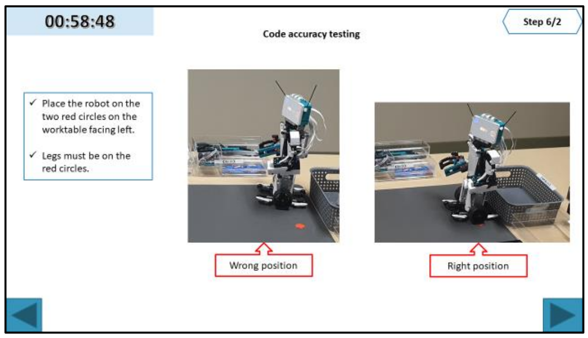

00:58:48
Step 1/2
✓ Open the coding interface window in Mindstorms® app.
✓ Check that the project name is “CAS I5.0 project”.

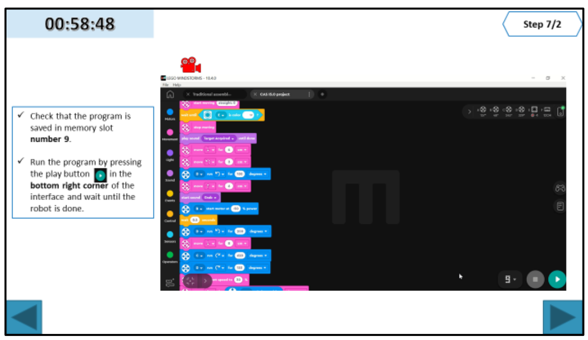

00:58:48
Step 2/2
✓ In the “Light” coding line number 1: change the center button light from red to yellow.

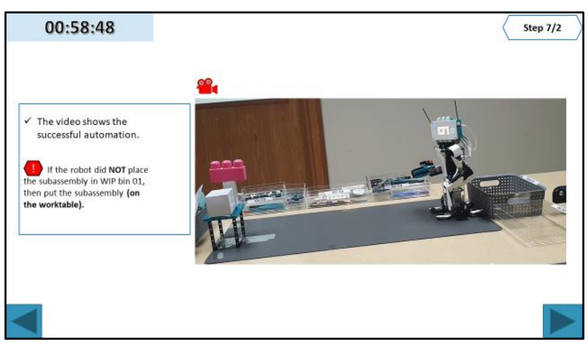

00:58:48
Step 3/2
✓ In the “Light” coding line number 2: change orientation from upright to left.

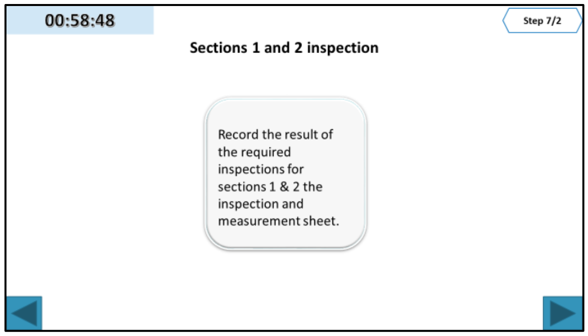

00:58:48
Step 4/2
✓ In the “motors” coding line number 4: use the keyboard and change the speed of motor C from 50% to 25%.

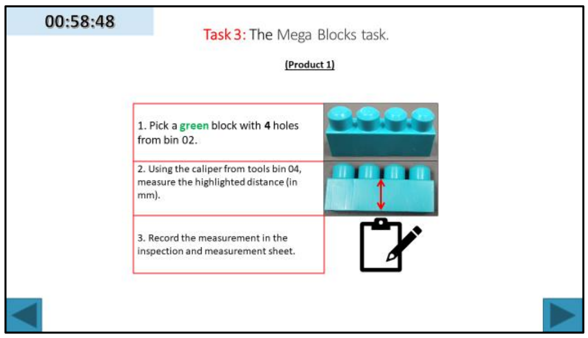

00:58:48
Step 5/2
In the combined "control" and "sensors" coding line change the "wait until color" from red to white.

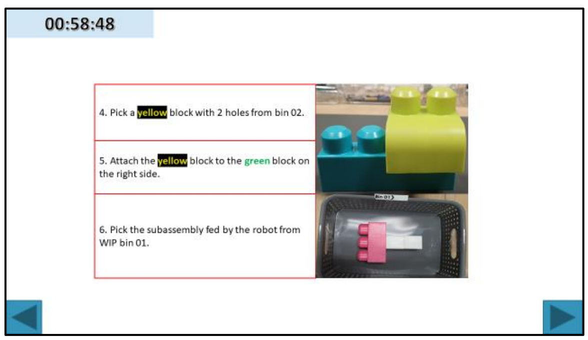

00:58:48
Code accuracy testing
Step 6/2
Place the robot on the two red circles on the worktable facing left.
Legs must be on the red circles.
Wrong position
Right position

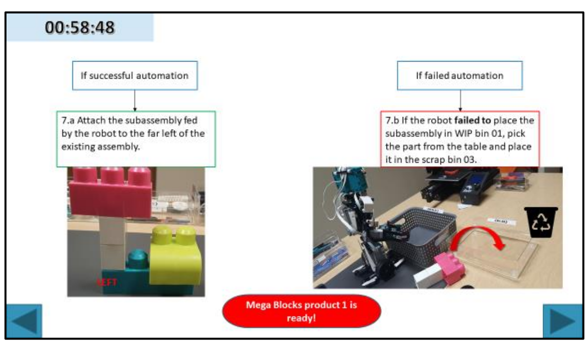

00:58:48
Step 7/2
Check that the program is saved in memory slot number 9.
Run the program by pressing the play button in the bottom right corner of the interface and wait until the robot is done.

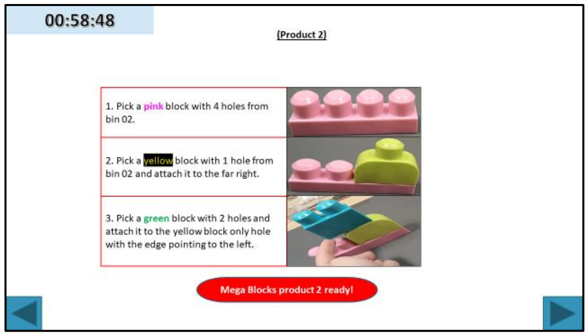

00:58:48
Step 7/2
The video shows the successful automation.
If the robot did NOT place the subassembly in WIP bin 01, then put the subassembly (on the worktable).

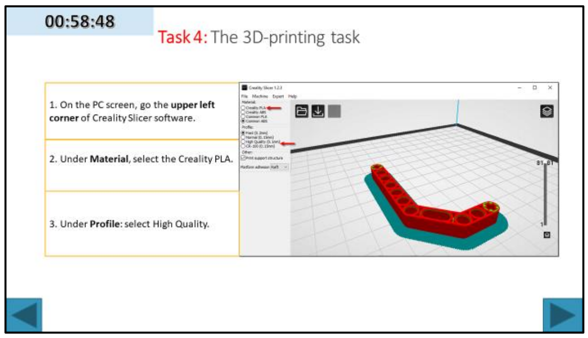

00:58:48
Step 7/2
Sections 1 and 2 inspection
Record the result of the required inspections for sections 1 & 2 the inspection and measurement sheet.

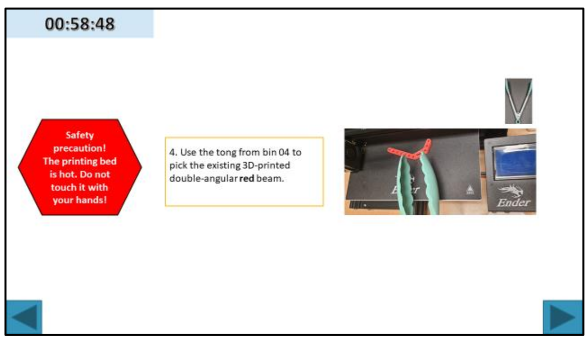

00:58:48
Task 3: The Mega Blocks task.
(Product 1)
1. Pick a green block with 4 holes from bin 02.
2. Using the caliper from tools bin 04, measure the highlighted distance (in mm).
3. Record the measurement in the inspection and measurement sheet.


00:58:48
4. Pick a yellow block with 2 holes from bin 02.
5. Attach the yellow block to the green block on the right side.
6. Pick the subassembly fed by the robot from WIP bin 01.

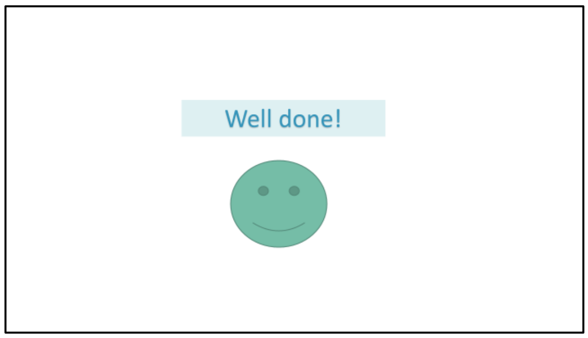

00:58:48
If successful automation
7.a Attach the subassembly fed by the robot to the far left of the existing assembly.
If failed automation
7.b If the robot failed to place the subassembly in WIP bin 01, pick the part from the table and place it in the scrap bin 03.
Mega Blocks product 1 is ready!


00:58:48
(Product 2)
1. Pick a pink block with 4 holes from bin 02.
2. Pick a yellow block with 1 hole from bin 02 and attach it to the far right.
3. Pick a green block with 2 holes and attach it to the yellow block only hole with the edge pointing to the left.
Mega Blocks product 2 ready!


00:58:48
Task 4: The 3D-printing task
1. On the PC screen, go the upper left corner of Creality Slicer software.
2. Under Material, select the Creality PLA.
3. Under Profile: select High Quality.


00:58:48
Safety precaution! The printing bed is hot. Do not touch it with your hands!
4. Use the tong from bin 04 to pick the existing 3D-printed double-angular red beam.
Ender


00:58:48
5. Using the caliper, measure the 3D-printed beam's thickness and record it in the inspection and measurement sheet.
Beams thickness


Well done!

APPENDIX J

CAS INTERFACE TIMER CODE

```
Sub countdown()
Dim time As Date
time = Now()

Dim count As Integer
count = ActivePresentation.Slides(4).Shapes("timelimit").TextFrame.TextRange
time = DateAdd("s", count, time)

Do Until time < Now()
DoEvents

For i = 4 To 26
ActivePresentation.Slides(i).Shapes("countdown").TextFrame.TextRange =
Format((time - Now()), "hh:mm:ss")
Next i

If time < Now() Then
For i = 4 To 26
```

```
ActivePresentation.Slides(4).Shapes("countdown").TextFrame.TextRange =
"Time up!"
Next i
ActivePresentation.SlideShowWindow.View.GotoSlide (27)
End If

Loop

End Sub
```

APPENDIX K

EXPERIMENT 2 INSPECTION AND MEASUREMENT SHEET

Inspection and measurements sheet

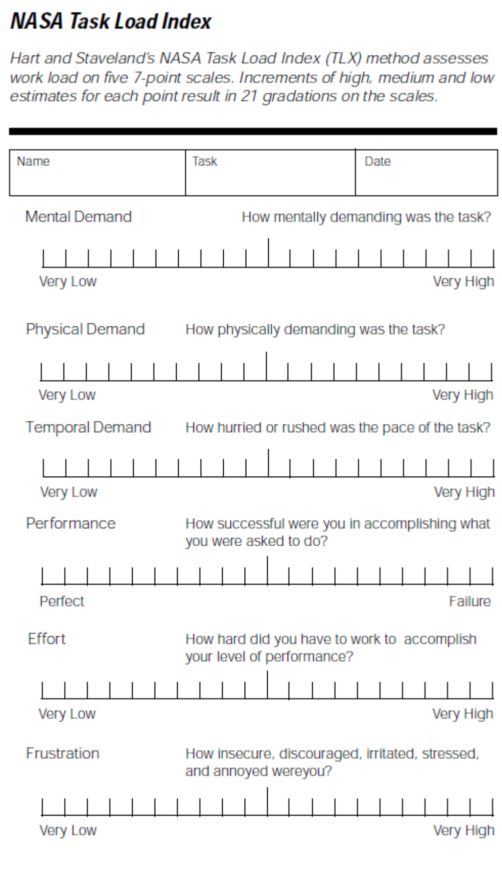
Section number	Inspection criteria	Inspection result (pass/fail)
1 & 2	The claw is securely fixed on the arm subassembly.	
1 & 2	The robot grabbed the Mega Blocks subassembly from the activity table.	
1 & 2	The robot placed the subassembly in bin 01.	

Section number	Step and part	Measurement (mm)
3	Step 2: green block highlighted distance.	
4	Step 5: 3D-printed beam thickness.	

Figure K-17: Experiment 2 inspection and measurement sheet.

APPENDIX L

NASA-TLX TEST



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure L-18: NASA-TLX test (paper version).

APPENDIX M

POST STUDY SYSTEM USABILITY QUESTIONNAIRE

The IBM Post Study System Usability Questionnaire (PSSUQ)

This questionnaire, which starts on the following page, gives you an opportunity to tell us your reactions to the MA5.0 Cognitive Assistance System you used. Your responses will help us understand what aspects of the system you are particularly concerned about and the aspects that satisfy you.

To as great a degree as possible, think about all the tasks that you have done with the system while you answer these questions.

Please read each statement and indicate how strongly you agree or disagree with the statement by circling a number on the scale. If a statement does not apply to you, circle N/A. Please write comments to elaborate on your answers.

After you have completed this questionnaire, I'll go over your answers with you to make sure I understand all of your responses.

Thank you!

System Use (SYSUSE) Section: items 1 through 8

1. Overall, I am satisfied with how easy it is to use this system.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

2. It was simple to use this system.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

3. I could effectively complete the tasks and scenarios using this system.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

4. I was able to complete the tasks and scenarios quickly using this system.

STRONGLY AGREE	1	2	3	4	5	6	7	STRONGLY DISAGREE

COMMENTS:

5. I was able to efficiently complete the tasks and scenarios using this system.

STRONGLY AGREE	1	2	3	4	5	6	7	STRONGLY DISAGREE

COMMENTS:

6. I felt comfortable using this system.

STRONGLY AGREE	1	2	3	4	5	6	7	STRONGLY DISAGREE

COMMENTS:

7. It was easy to learn to use this system.

STRONGLY AGREE	1	2	3	4	5	6	7	STRONGLY DISAGREE

COMMENTS:

8. I believe I could become productive quickly using this system.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

Information Quality (INFOQUA) Section items 9 through 15

9. The system gave error messages that clearly told me how to fix problems.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

10. Whenever I made a mistake using the system, I could recover easily and quickly.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

11. The information (such as on-line help, on-screen messages and other documentation) provided with this system was clear.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

12. It was easy to find the information I needed.

STRONGLY AGREE	1	2	3	4	5	6	7	STRONGLY DISAGREE

COMMENTS:

13. The information provided for the system was easy to understand.

STRONGLY AGREE	1	2	3	4	5	6	7	STRONGLY DISAGREE

COMMENTS:

14. The information was effective in helping me complete the tasks and scenarios.

STRONGLY AGREE	1	2	3	4	5	6	7	STRONGLY DISAGREE

COMMENTS:

15. The organization of information on the system screens was clear.

STRONGLY AGREE	1	2	3	4	5	6	7	STRONGLY DISAGREE

COMMENTS:

Interface Quality (INTERQUAL) Section Items 16 through 18

Note: *The interface includes those items that you use to interact with the system. For example, some components of the interface are the keyboard, the mouse, the screens (including their use of graphics and language).*

16. The interface of this system was pleasant.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

17. I liked using the interface of this system.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

18. This system has all the functions and capabilities I expect it to have.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

OVERALL Section

19. Overall, I am satisfied with this system.

STRONGLY AGREE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**STRONGLY DISAGREE**

COMMENTS:

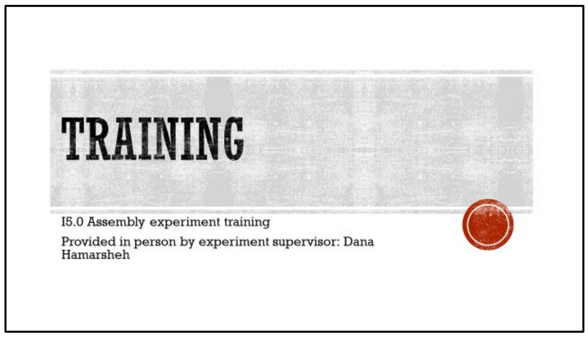
Note: Overall score will include all items 1 through 19.

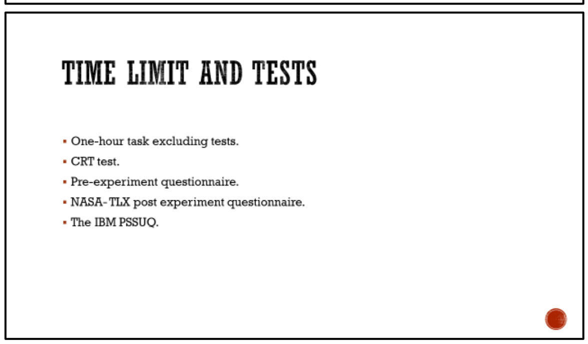
Score:

Section Name	**Average the Responses to**	**Resulting Score**
SYSUSE	Items 1 through 8	
INFOQUAL	Items 9 through 15	
INTERQUAL	16 through 18	
OVERALL	Items 1 through 19	

APPENDIX N

EXPERMENT 2 TRAINING





EYE TRACKING

- Calibration.
- Range of motion (wired device).

I5.0 WORK ENVIRONMENT COMPONENTS

- The bins (numbered) and parts.
- Parts catalogue (1:1) ratio.

ASSISTANCE SYSTEM TABLET

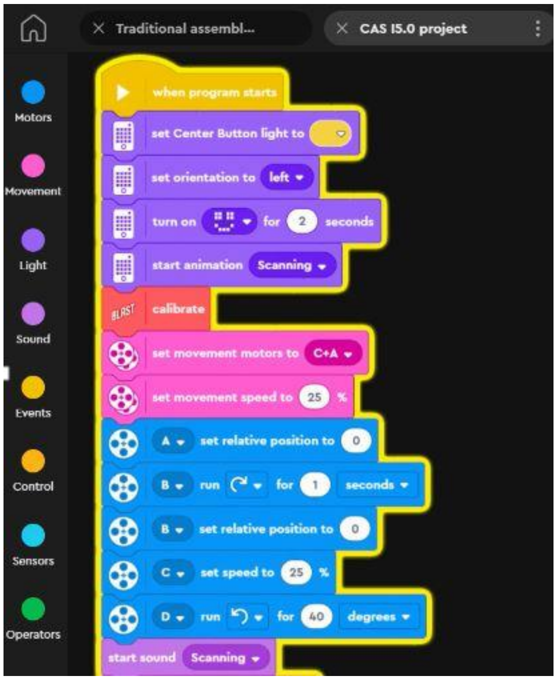
- Switching between screens.
- Playing video instructions.

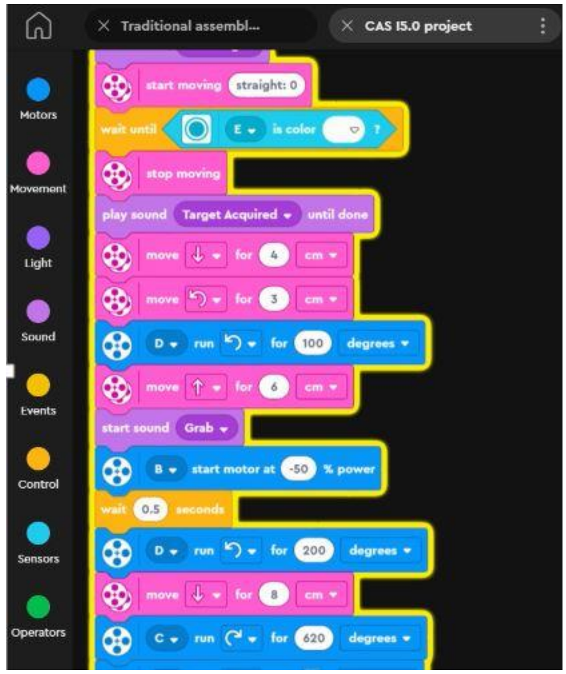
NOTES

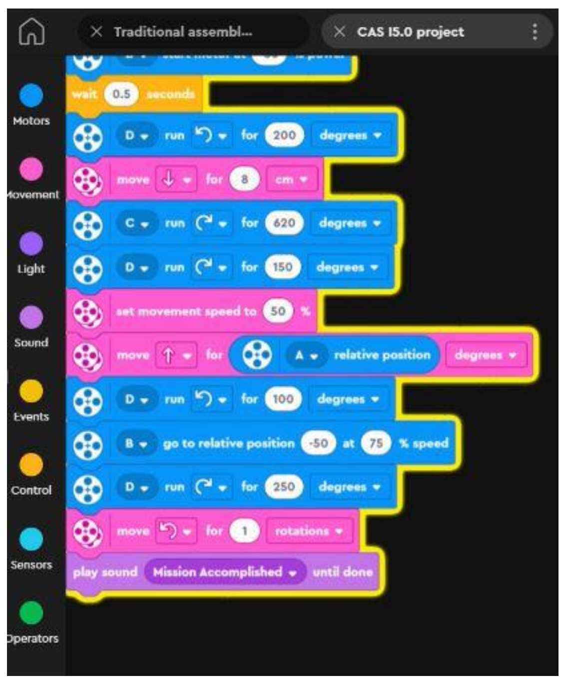
- No communication with the lab attendant is allowed during the experiment, during pre-experiment questionnaires or post-experiment questionnaires.
- If you face any technical problems you can notify the lab attendant.

APPENDIX O

THE ROBOT AUTOMATION CODE




Traditional assembl...
CAS I5.0 project
Motors
Movement
Light
Sound
Events
Control
Sensors
Operators
start moving straight: 0
wait until E is color ?
stop moving
play sound Target Acquired until done
move for 4 cm
move for 3 cm
D run for 100 degrees
move for 6 cm
start sound Grab
B start motor at -50 % power
wait 0.5 seconds
D run for 200 degrees
move for 8 cm
C run for 620 degrees


Traditional assembl...
CAS I5.0 project
Motors
Light
Sound
Events
Control
Sensors
wait 0.5 seconds
D run for 200 degrees
move for 8 cm
C run for 620 degrees
D run for 150 degrees
set movement speed to 50 %
move for A relative position degrees
D run for 100 degrees
B go to relative position -50 at 75 % speed
D run for 250 degrees
move for 1 rotations
play sound Mission Accomplished until done

BIBLIOGRAPHY

[1] B. G. Mark, E. Rauch, and D. T. Matt, "Industrial Assistance Systems to Enhance Human–Machine Interaction and Operator's Capabilities in Assembly," in Implementing Industry 4.0 in SMEs, Palgrave Macmillan, Cham, 2021, pp. 129–161.

[2] A. Miqueo, M. Torralba, and J. A. Yagüe-Fabra, "Lean manual assembly 4.0: A systematic review," Applied Sciences, vol. 10, no. 23, p. 8555, 2020.

[3] L. Nolting et al., "Generating transparency in the worldwide use of the terminology industry 4.0," Applied Sciences, vol. 9, no. 21, p. 4659, 2019.

[4] M. Rüßmann et al., "Industry 4.0: The future of productivity and growth in manufacturing industries," Boston consulting group, vol. 9, no. 1, pp. 54–89, 2015.

[5] Y. Cohen, H. Naseraldin, A. Chaudhuri, and F. Pilati, "Assembly systems in Industry 4.0 era: a road map to understand Assembly 4.0," The International Journal of Advanced Manufacturing Technology, vol. 105, no. 9, pp. 4037–4054, 2019.

[6] T. Wagner, C. Herrmann, and S. Thiede, "Industry 4.0 impacts on lean production systems," Procedia CIRP, vol. 63, pp. 125–131, 2017.

[7] P. K. R. Maddikunta et al., "Industry 5.0: A survey on enabling technologies and potential applications," J Ind Inf Integr, vol. 26, p. 100257, 2022.

[8] L. Allender, "Modeling human performance: Impacting system design, performance, and cost," Simulation Series, vol. 32, no. 3, pp. 139–144, 2000.

[9] E. Hollnagel, "Cognitive ergonomics: it's all in the mind," Ergonomics, vol. 40, no. 10, pp. 1170–1182, 1997.

[10] N. A. Stanton, P. M. Salmon, L. A. Rafferty, G. H. Walker, C. Baber, and D. P. Jenkins, Human factors methods: a practical guide for engineering and design. CRC Press, 2017.

[11] D. Kahneman and S. Frederick, "Representativeness revisited: Attribute substitution in intuitive judgment," Heuristics and biases: The psychology of intuitive judgment, vol. 49, p. 81, 2002.

[12] D. Kahneman, Thinking, fast and slow. Macmillan, 2011.

[13] A. Tversky and D. Kahneman, "Judgment under uncertainty: Heuristics and biases," Science (1979), vol. 185, no. 4157, pp. 1124–1131, 1974.

[14] F. Gino and G. Pisano, "Toward a theory of behavioral operations," Manufacturing & Service Operations Management, vol. 10, no. 4, pp. 676–691, 2008.

[15] K. Hozak and E. O. Olsen, "Lean psychology and the theories of 'Thinking, Fast and Slow," International Journal of Lean Six Sigma, 2015.

[16] J. Bendul, "Understanding the meaning of human perception and cognitive biases for production planning and control," IFAC-PapersOnLine, vol. 52, no. 13, pp. 2201–2206, 2019.

[17] M. Cristofaro, L. Leoni, and P. L. Giardino, "Cognitive biases' influence on employees' product creativity and product performance: evidences from Italian manufacturing technology firms," Journal of Manufacturing Technology Management, 2021.

[18] E. I. Hoppe and D. J. Kusterer, "Behavioral biases and cognitive reflection," Econ Lett, vol. 110, no. 2, pp. 97–100, 2011.

[19] C. Berlin, M. W. Bergman, M. B. Chafi, A.-C. Falck, and R. Örtengren, "A Systemic Overview of Factors Affecting the Cognitive Performance of Industrial Manual Assembly Workers," in Congress of the International Ergonomics Association, 2021, pp. 371–381.

[20] K. G. Swift and J. D. Booker, Manufacturing process selection handbook. Butterworth-Heinemann, 2013.

[21] J. Lindblom and P. Thorvald, "Towards a framework for reducing cognitive load in manufacturing personnel," Advances in cognitive engineering and neuroergonomics, vol. 11, pp. 233–244, 2014.

[22] A. Brolin, P. Thorvald, and K. Case, "Experimental study of cognitive aspects affecting human performance in manual assembly," Prod Manuf Res, vol. 5, no. 1, pp. 141–163, 2017.

[23] P. Thorvald and J. Lindblom, "Initial development of a cognitive load assessment tool," in The 5th AHFE International conference on applied human factors and ergonomics, AHFE, 2014, pp. 223–232.

[24] B. B. Van Acker et al., "Development and validation of a behavioural video coding scheme for detecting mental workload in manual assembly," Ergonomics, vol. 64, no. 1, pp. 78–102, 2021.

[25] M. De Rivecourt, M. N. Kuperus, W. J. Post, and L. J. M. Mulder, "Cardiovascular and eye activity measures as indices for momentary changes in mental effort during simulated flight," Ergonomics, vol. 51, no. 9, pp. 1295–1319, 2008.

[26] L. R. Fournier, G. F. Wilson, and C. R. Swain, "Electrophysiological, behavioral, and subjective indexes of workload when performing multiple tasks: manipulations of task difficulty and training," International Journal of Psychophysiology, vol. 31, no. 2, pp. 129–145, 1999.

[27] L. Finsen, K. Søgaard, C. Jensen, V. Borg, and H. Christensen, "Muscle activity and cardiovascular response during computer-mouse work with and without memory demands," Ergonomics, vol. 44, no. 14, pp. 1312–1329, 2001.

[28] T. Sosnowski, B. Krzywosz-Rynkiewicz, and J. Roguska, "Program running versus problem solving: Mental task effect on tonic heart rate," Psychophysiology, vol. 41, no. 3, pp. 467–475, 2004.

[29] J. M. Splawn and M. E. Miller, "Prediction of perceived workload from task performance and heart rate measures," in Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2013, vol. 57, no. 1, pp. 778–782.

[30] M. Causse, J.-M. Sénard, J. F. Démonet, and J. Pastor, "Monitoring cognitive and emotional processes through pupil and cardiac response during dynamic versus logical task," Appl Psychophysiol Biofeedback, vol. 35, no. 2, pp. 115–123, 2010.

[31] J. A. Veltman and A. W. K. Gaillard, "Physiological indices of workload in a simulated flight task," Biol Psychol, vol. 42, no. 3, pp. 323–342, 1996.

[32] R. L. Charles and J. Nixon, "Measuring mental workload using physiological measures: A systematic review," Appl Ergon, vol. 74, pp. 221–232, 2019.

[33] M. L. Mele and S. Federici, "Gaze and eye-tracking solutions for psychological research," Cogn Process, vol. 13, no. 1, pp. 261–265, 2012.

[34] G. Anders, "Pilot's attention allocation during approach and landing- Eye-and head-tracking research in an A 330 full flight simulator," Focusing Attention on Aviation Safety, 2001.

[35] L. C. Thomas and C. D. Wickens, "Eye-tracking and individual differences in off-normal event detection when flying with a synthetic vision system display," in Proceedings of the human factors and ergonomics society annual meeting, 2004, vol. 48, no. 1, pp. 223–227.

[36] A. Poole and L. J. Ball, "Eye tracking in HCI and usability research," in Encyclopedia of human computer interaction, IGI global, 2006, pp. 211–219.

[37] M.-A. Kim, H.-J. Yoo, G. Ares, and H.-S. Lee, "Effect of thinking style and consumption purpose on food choice: A case study with yogurt using a discrete choice experiment and eye-tracking," Food Qual Prefer, vol. 86, p. 104025, 2020.

[38] D. C. Evans and M. Fendley, "A multi-measure approach for connecting cognitive workload and automation," Int J Hum Comput Stud, vol. 97, pp. 182–189, 2017.

[39] A. T. Duchowski, "A breadth-first survey of eye-tracking applications," Behavior Research Methods, Instruments, & Computers, vol. 34, no. 4, pp. 455–470, 2002.

[40] O. Palinko, A. L. Kun, A. Shyrokov, and P. Heeman, "Estimating Cognitive Load Using Remote Eye Tracking in a Driving Simulator," in Proceedings of the 2010 symposium on eye-tracking research & applications, 2010, pp. 141–144.

[41] J. Niemann, C. Fussenecker, M. Schlösser, and E. Ocakci, "The Workers Perspective-Eye Tracking in Production Environments," Acta Technica Napocensis-Series: Applied Mathematics, Mechanics, and Engineering, vol. 64, no. 1-S1, 2021.

[42] A. T. Duchowski and A. T. Duchowski, Eye tracking methodology: Theory and practice. Springer, 2017.

[43] D. Kaune, "An eye tracking supported video analysis for assembly optimization at BARBIERI electronic snc," 2018. (Project Report). https://smartminifactory.it/wp-content/uploads/2018/10/Study-Project_Daniel-Kaune_without-appendix.pdf.

[44] G. Dragoi, A. Draghici, S. M. Rosu, A. Radovici, and C. E. Cotet, "Professional risk assessment using virtual enterprise network support for knowledge bases development," in International conference on enterprise information systems, 2010, pp. 168–177.

[45] G. Dragoi, A. Draghici, S. M. Rosu, and C. E. Cotet, "Virtual product development in university-enterprise partnership," Information Resources Management Journal (IRMJ), vol. 23, no. 3, pp. 43–59, 2010.

[46] S. Hasanzadeh, B. Esmaeili, and M. D. Dodd, "Measuring construction workers' real-time situation awareness using mobile eye-tracking," in Construction Research Congress 2016, 2016, pp. 2894–2904.

[47] M. V Yousefi, E. Karan, A. Mohammadpour, and S. Asadi, "Implementing eye tracking technology in the construction process," in 51st ASC Annual International Conference Proceedings, 2015, pp. 752–759.

[48] S. Hasanzadeh, B. Esmaeili, and M. D. Dodd, "Measuring the impacts of safety knowledge on construction workers' attentional allocation and hazard detection using remote eye-tracking technology," Journal of management in engineering, vol. 33, no. 5, p. 4017024, 2017.

[49] Q. Lohmeyer, S. Matthiesen, and M. Meboldt, "Task-dependent Visual Behaviour of Engineering Designers-an Eye Tracking Experiment," in DS 77: Proceedings of the DESIGN 2014 13th International Design Conference, 2014, pp. 549–558.

[50] Q. Lohmeyer and M. Meboldt, "How we understand engineering drawings: an eye tracking study investigating skimming and scrutinizing sequences," International

Conference on Engineering Design, ICED15 27-30 July 2015, Politecnico Di Milano, Italy

[51] I. Jeelani, K. Han, and A. Albert, "Automating and scaling personalized safety training using eye-tracking data," Autom Constr, vol. 93, pp. 63–77, 2018.

[52] J. Li et al., "Identification and classification of construction equipment operators' mental fatigue using wearable eye-tracking technology," Autom Constr, vol. 109, p. 103000, 2020.

[53] M. Lušić, C. Fischer, K. S. Braz, M. Alam, R. Hornfeck, and J. Franke, "Static versus dynamic provision of worker information in manual assembly: a comparative study using eye tracking to investigate the impact on productivity and added value based on industrial case examples," Procedia CIRP, vol. 57, pp. 504–509, 2016.

[54] Y. Borgianni, E. Rauch, L. Maccioni, and B. G. Mark, "User experience analysis in industry 4.0-the use of biometric devices in engineering design and manufacturing," in 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2018, pp. 192–196.

[55] J. Nakamura, S. Nagayoshi, and N. Komiya, "Cognitive Biases as Clues to Skill Acquisition in Manufacturing Industry," in 2021 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2021, pp. 1275–1278.

[56] P. Mehta, "Employing eye-tracking, screen capture and artifact analysis methods to characterize re-design for Additive Manufacturing behaviors," 2019. MS Thesis, Pennsylvania State University. https://etda.libraries.psu.edu/catalog/17337pum339.

[57] P. Mehta, M. Malviya, C. McComb, G. Manogharan, and C. G. P. Berdanier, "Mining Design Heuristics for Additive Manufacturing Via Eye-Tracking Methods and Hidden Markov Modeling," Journal of Mechanical Design, vol. 142, no. 12, 2020.

[58] Y. Borgianni, L. Maccioni, and D. Basso, "Exploratory study on the perception of additively manufactured end-use products with specific questionnaires and eye-tracking," International Journal on Interactive Design and Manufacturing (IJIDeM), vol. 13, no. 2, pp. 743–759, 2019.

[59] A. Haleem and M. Javaid, "Additive manufacturing applications in industry 4.0: a review," Journal of Industrial Integration and Management, vol. 4, no. 04, p. 1930001, 2019.

[60] M. Kassner, W. Patera, and A. Bulling, "Pupil: an open source platform for pervasive eye tracking and mobile gaze-based interaction," in Proceedings of the

2014 ACM international joint conference on pervasive and ubiquitous computing: Adjunct publication, 2014, pp. 1151–1160.

[61] B. Lotter and H.-P. Wiendahl, "Changeable and reconfigurable assembly systems," Changeable and reconfigurable manufacturing systems, pp. 127–142, 2009.

[62] S. Frederick, "Cognitive reflection and decision making," Journal of Economic perspectives, vol. 19, no. 4, pp. 25–42, 2005.

[63] M. E. Toplak, R. F. West, and K. E. Stanovich, "Assessing miserly information processing: An expansion of the Cognitive Reflection Test," Think Reason, vol. 20, no. 2, pp. 147–168, 2014.

[64] M. R. Endsley and M. D. Rodgers, "Distribution of attention, situation awareness, and workload in a passive air traffic control task: Implications for operational errors and automation," Federal Aviation Administration Washington D.c. Office of Aviation Medicine, 1997.

[65] U. M. Dilberoglu, B. Gharehpapagh, U. Yaman, and M. Dolen, "The role of additive manufacturing in the era of industry 4.0," Procedia Manuf, vol. 11, pp. 545–554, 2017.

[66] A. Carpignano and M. Piccini, "Cognitive theories and engineering approaches for safety assessment and design of automated systems: a case study of a power plant," Cognition, Technology & Work, vol. 1, no. 1, pp. 47–61, 1999.

[67] J. Kirakowski, "The use of questionnaire methods for usability assessment." 1994. (ResearchGate report). https://www.researchgate.net/profile/Jurek-Kirakowski/project/SUMI-Questionnaire/attachment/5ae302e1b53d2f63c3c86f11/AS:619982895456256@1524826849051/download/SUMIPAPP.pdf.

[68] A. Assila and H. Ezzedine, "Standardized usability questionnaires: Features and quality focus," Electronic Journal of Computer Science and Information Technology, vol. 6, no. 1, 2016.

[69] A. Hodrien and T. P. Fernando, "A review of post-study and post-task subjective questionnaires to guide assessment of system usability," J Usability Stud, vol. 16, no. 3, pp. 203–232, 2021.

[70] M. F. Land and S. Furneaux, "The knowledge base of the oculomotor system," Philos Trans R Soc Lond B Biol Sci, vol. 352, no. 1358, pp. 1231–1239, 1997.

[71] G. Marquart, C. Cabrall, and J. de Winter, "Review of eye-related measures of drivers' mental workload," Procedia Manuf, vol. 3, pp. 2854–2861, 2015.

[72] K. Holmqvist, M. Nyström, R. Andersson, R. Dewhurst, H. Jarodzka, and J. Van de Weijer, Eye tracking: A comprehensive guide to methods and measures. OUP Oxford, 2011.

[73] Y. Torres, S. Nadeau, and K. Landau, "Classification and quantification of human error in manufacturing: a case study in complex manual assembly," Applied Sciences, vol. 11, no. 2, p. 749, 2021.