AN AMBIENT AGENT MODEL FOR READING COMPANION ROBOT

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Abstrak

Membaca pada asasnya adalah tugas penyelesaian masalah. Berdasarkan apa yang dibaca, seperti penyelesaian masalah, ia memerlukan usaha, perancangan, pemantauan kendiri, pemilihan strategi, dan refleksi. Tambahan lagi, semakin pembaca cuba menyelesaikan masalah yang sukar, dengan bahan bacaan yang semakin rumit, maka ia memerlukan usaha yang lebih dan mencabar kognitif. Untuk menangani isu ini, robot peneman boleh digunakan untuk membantu pembaca dalam menyelesaikan tugas membaca yang sukar dengan menjadikan proses membaca lebih menyeronokkan dan bermakna. Robot sebegini memerlukan model agen ambien, yang memantau keupayaan kognitif pembaca yang mana ia melibatkan tugas yang lebih kompleks dan interaksi dinamik antara manusia dan persekitaran. Model agen ambien beban kognitif pada masa kini yang dibangunkan tidak mempunyai keupayaan analitikal dan tidak diintegrasikan ke dalam robot peneman. Oleh sebab itu, kajian ini dijalankan untuk membangunkan satu model agen ambien bagi beban kognitif dan prestasi bacaan yang diintegrasikan ke dalam robot peneman bacaan. Aktiviti penyelidikan adalah berdasarkan Proses Penyelidikan RekaBentuk Sains, Pemodelan Berasaskan Agen, dan Rangkakerja Agen Ambien. Model cadangan ini telah dinilai melalui beberapa siri penentusahan dan pengesahsahihan. Proses penentusahan melibatkan penilaian keseimbangan dan analisa jejakan automatik untuk memastikan model ini menunjukkan tingkah laku yang realistik dan selaras dengan data empirikal dan sorotan kajian. Di samping itu, proses pengesahsahihan yang melibatkan eksperimen manusia telah membuktikan bahawa robot peneman bacaan berupaya mengurangkan bebanan kognitif semasa tugas membaca. Tambahan lagi, keputusan eksperimen menunjukkan bahawa dengan mengintegrasikan model agen ambien ke dalam robot peneman bacaan dapat menjadikan robot diterima sebagai teman sampingan digital sosial yang pintar, berguna, dan mampu memberikan motivasi. Sumbangan kajian menjadikan penyelidikan ini sebagai usaha baharu yang bertujuan merekabentuk aplikasi ambien berasaskan proses fizikal dan kognitif manusia. Di samping itu, penemuan ini dapat berfungsi sebagai satu prinsip rekabentuk robot peneman yang lebih realistik di masa hadapan.

Kata kunci: Model Agen Ambien, Beban Kognitif, Prestasi Membaca, Peneman Digital.

Abstract

Reading is essentially a problem-solving task. Based on what is read, like problem solving, it requires effort, planning, self-monitoring, strategy selection, and reflection. Also, as readers are trying to solve difficult problems, reading materials become more complex, thus demands more effort and challenges cognition. To address this issue, companion robots can be deployed to assist readers in solving difficult reading tasks by making reading process more enjoyable and meaningful. These robots require an ambient agent model, monitoring of a reader's cognitive demand as it could consist of more complex tasks and dynamic interactions between human and environment. Current cognitive load models are not developed in a form to have reasoning qualities and not integrated into companion robots. Thus, this study has been conducted to develop an ambient agent model of cognitive load and reading performance to be integrated into a reading companion robot. The research activities were based on Design Science Research Process, Agent-Based Modelling, and Ambient Agent Framework. The proposed model was evaluated through a series of verification and validation approaches. The verification process includes equilibria evaluation and automated trace analysis approaches to ensure the model exhibits realistic behaviours and in accordance to related empirical data and literature. On the other hand, validation process that involved human experiment proved that a reading companion robot was able to reduce cognitive load during demanding reading tasks. Moreover, experiments results indicated that the integration of an ambient agent model into a reading companion robot enabled the robot to be perceived as a social, intelligent, useful, and motivational digital side-kick. The study contribution makes it feasible for new endeavours that aim at designing ambient applications based on human's physical and cognitive process as an ambient agent model of cognitive load and reading performance was developed. Furthermore, it also helps in designing more realistic reading companion robots in the future.

Keywords: Ambient Agent Model, Cognitive Load, Reading Performance, Digital Companion.

Acknowledgement

"Education is the most powerful weapon which you can use to change the world."

Nelson Mandela

The end of my childhood dream is become visible by the time I start writing this acknowledgment. I have always dreamt of obtaining a good education to dive in adding little spices to the mind-blowing jar of scientific knowledge. I will not deny people inspirations foster my aspiration and drove me thousands of miles away from home country (Mesopotamia) to Malaysia just to make my old dream comes true. And after four years of hate-love relationship with my thesis, all I can say is, I am happy, thankful, and proud of being able to make a little contribution in the fields of Artificial Intelligence and Robotic Technology.

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

Intelligent artefacts have always received important attention among many scientists, engineers, and innovators to improve quality of life and facilitate daily activities through understanding human physical and cognitive processes (Costa, Novais, & Julian, 2018). These new endeavours of creating intelligent and knowledgeable artefacts to the great extent are becoming a dispensable part towards broaden the landscape of state of the arts in intelligent applications. For instance, in ambient intelligence paradigm (AmI), which is a discipline that brings intelligence to our living environments and makes those environments responsive to our needs, intelligent applications were developed extensively to aid humans by making their surrounding environments more sensible to response in a timely fashion. Such AmI applications can be seen in a wide range of application domains, such as in education (Zhu, Yu, & Riezebos, 2016; Corno, De Russis, & Sáenz, 2017; Durães, Castro, Bajo, & Novais, 2017), healthcare interventions (Al-Shaqi, Mourshed, & Rezgui, 2016; Dey & Ashour, 2017; Durães et al., 2017), public transportations (Nakashima, Hirata, & Ochiai, 2017), emergency services (Kleinberger, Jedlitschka, Storf, Steinbach-Nordmann, & Prueckner, 2009), and robotics (Bellotto, Fernandez-Carmona, & Cosar, 2017).

However, with the new endeavours to enhance the state of the arts of these smart applications (Treur, 2016b), these AmI applications need to acquire additional information related to human functioning to provide relevant assistance in a knowledgeable manner. In other words, AmI applications were initially developed merely based on the sensor-based and data fusion information acquisition, therefore more intelligent applications rely on the availability of an adequate knowledge for the analysis of human functioning (Bosse, Both, Gerritsen, Hoogendoorn, & Treur, 2012; Bosse, Duell, Memon, Treur, & van der Wal, 2017). To discern this new ability, different spectrums from cognitive, bio-psychology, neuroscience, and bio-medical science using an agent based modelling approach have been modelled to provide a comprehensive knowledge on physical and cognitive aspects of human and this knowledge can be combined as core foundations in creating ambient intelligence applications (Aziz, 2016). Furthermore, by integrating explicit knowledge about physical and cognitive processes of humans with the ability to perform reasoning about these processes into AmI applications, then these applications will have a better understanding of humans. Thus, this prime ability can be of importance in performing a more in depth-analysis of the human functioning (Mollee & Klein, 2017b) to place intelligent and proactive supports that later can be seen as a form of social intelligence (Aarts & De Ruyter, 2009; Bosse, Callaghan, & Lukowicz, 2010; Augello et al., 2018).

There is a large volume of successful attempts were made to develop ambient intelligent agent applications by modelling the dynamics of human cognitive and physical processes (Duell, 2016). These applications were designed to provide intelligent support in an informed manner (e.g., by utilizing cognitive and physical states of humans). For example models (1) to support people in making decisions during emergency cases (Bosse & Sharpanskykh, 2010), (2) of driver behaviour to create an intelligent driving assistant (Mustapha, Yusof, & Aziz, 2017), (3) of frustration and misbehaviours of stranded passengers for the operator training simulator (Medeiros & van der Wal, 2017), (4) for stressed person in social media context to create virtual friends to alleviate stress (Medeiros & Bosse, 2017), and (5) human behaviour to promote physical activity (Klein, Manzoor, & Mollee, 2017).

These types of ambient agent models also could be integrated to execute a different number of intelligent agent applications such as recommender systems, smart homes, intelligent cars, and companion robots (Treur, 2016b).

In another spectrum, the robotic research domain has witnessed an exponential growth where robots have been shifted drastically from industrial settings towards developing more sophisticated robots that can interact with users through social cues (Breazeal, Dautenhahn, & Kanda, 2016). As a result, it has a new type of robot to help people called companion robots. Companion robots are designed to interact with people in human-centric manners and to operate within human friendly settings. These robots engage with people in an interpersonal manner, communicating and coordinating their behaviours with humans through verbal, non-verbal, or affective modalities (Matarić & Scassellati, 2016). Moreover, companion robots have been extensively deployed in a number of domains including education, therapy, entertainment, and human assistance (Eguchi & Okada, 2017; Broadbent et al., 2018; Martinez-Martin & del Pobil, 2018; Riva, 2018; Santos et al., 2018). Currently, among well-known commercially available companion robots are Nao and Peeper developed by SoftBank Robotics (formerly Aldebaran Robotics), Zenbo developed by ASUS Inc. and JIBO developed by JIBO Inc.

It is important to consider in designing similar kind of robots, a deep understanding of human intelligence across multiple dimensions (i.e., cognitive, affective, physical, social, etc.) is required to ensure these robots are able to execute its intended design as a beneficial role in human living environment (Breazeal et al., 2016; Breazeal, 2017). Thus, a first conclusion can be derived that human functioning models can be of importance in designing companion robots where these models can serve as one of the core mechanisms to determine the functionality of the designed robots. In the light of the preceded explanations, a new study was made to design a reading companion robot that can socially and intelligently support readers during demanding reading tasks.

This study is essential due to the importance of reading process in daily lives. Reading is considered as a significant process that people usually perform for various purposes in their daily lives. For example, reading for pleasure (pastime or hobby) requires lesser concentration compared to reading for an exam or technical quests. This is also hampered by some issues as unable to stay focused due to the experienced cognitive load (Sweller, Ayres, & Kalyuga, 2011; Sweller, 2016). In this sense, a cognitive load concept is the amount of mental efforts readers experience and generate to accomplish a particular critical task. Basically, the notion of cognitive overload is related to the nature of limited working memory capacity and its prolonged duration of holding new acquired information (Sweller, 2017). In some circumstances, a combination of certain factors such as environment (e.g., coldness, heat, and noise), reading materials (printed vs. electronic) and complexity of the assigned task impair the human cognitive capacity that later dampen learning performance (Choi et al., 2014).

Furthermore, reading to acquire new knowledge requires high efforts and it always accompanied with negative factors such as cognitive overload, disengagement, exhaustion, and lack of motivation. These aforementioned factors have relayed negative effects on learning outcomes (Paas, Tuovinen, van Merriënboer, & Aubteen Darabi, 2005; Schnotz, Fries, & Horz, 2009; Mizuno et al., 2011; Vandewaetere & Clarebout, 2013; Gillmor, Poggio, & Embretson, 2015; Sweller, 2017).

These issues have been widely investigated in different aspects of readers and learners' perspectives with special focus to create personalized intelligent technologies that able to assist and increase readers' learning gains. One of the most prominent examples is intelligent tutoring applications (Khan, Graf, Weippl, & Tjoa, 2010; Bradáč & Kostolányová, 2017). Albeit its popularity, most of the tutoring technologies are not equipped with functioning models of reader's cognitive states and processes as those applications are relying on sensor-based information as a basis for decision-making processes.

Thus, in the realm of designing a reading companion robot, an interplay between various domains is needed. Figure 1.1 depicts some related research fields that have been explored in attaining the intended goal. In further examination, the agent-based modelling techniques, as one of the artificial intelligence domains, have been implemented as a first step to model human's physical and cognitive states (i.e., to obtain human functioning models). The interplay between psychology, computational sciences, and cognitive science is required to form an aspect of understanding related to the problem domain. Later, the obtained domain model can be formalized to enable reasoning mechanisms of any digital artefacts (e.g. companion robots). Furthermore, a number of relevant design issues in companion robots has been investigated as well.

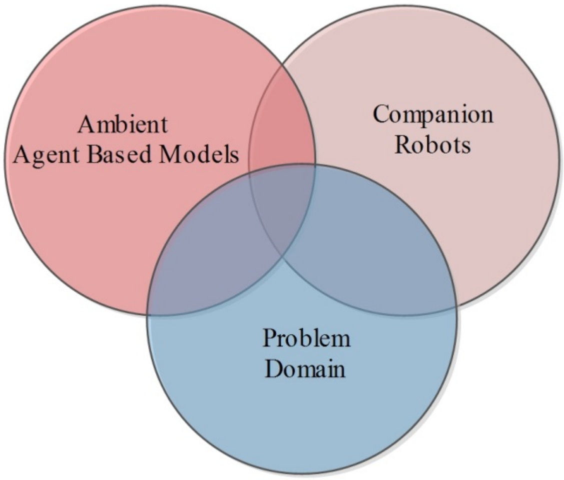

Figure 1.1. Cross-Disciplinary Research Fields

Based on previously mentioned issues, this study aims at developing an ambient agent model of cognitive load and reading performance to explain the mechanisms of a computational integration between the human functioning model of cognitive load and reading performance with a companion robot.

1.2 Problem Statement

Today, people live in an era where smart technologies are becoming an inevitable lifestyle as these technologies augment human capabilities. However, with the rapid advancement in technology, current paradigms are towards making socially intelligent applications, where these applications are able to make living environments more sensible, sociable, and supportive towards human's needs (Heras, Palanca, & Chesñevar, 2018). The interaction between ambient intelligence (AmI) research fields with agent technologies has broaden new landscapes and challenges in creating intelligent applications that capable to understand human's specific needs. This form of understanding encompasses the analysis of both human physical and cognitive states. Based on this human functioning knowledge, intelligent software agents will be able to provide support and intervention in a human-like manner (Aziz, 2016; Duell, 2016).

Moreover, the sensor-based information systems alone are not adequate enough to offer detailed analysis on the dynamic of human's physical and cognitive processes (Bosse, Callaghan, et al., 2010). This is due to the human functioning models are complex in nature, but it forms essential components to be integrated in developing intelligent agent applications. To this end, vast literature has presented a significant amount of current works related to the human functioning models and how those models can serve as reasoning engines for intelligent agents (Bosse et al., 2013; Aziz, 2016; Duell, 2016; Treur, 2016b). It is noteworthy to mention that these models can be integrated into both virtual and physical agents such as virtual characters and robots (Treur, 2016).

Most of the developed models were only used to study the dynamics of human physical and cognitive behaviours (Bosse et al., 2012, 2017; Duell, 2016; Medeiros & Bosse, 2017; Prochazkova & Kret, 2017; Xu et al., 2017; Medeiros & van der Wal, 2017; Mollee & Klein, 2017; Mustapha et al., 2017) through a series of computer simulations. However, three exceptional cases were found where these models were integrated with virtual agent technologies to assist human in the case of depression (Both, Hoogendoorn, Klein, & Treur, 2009), aggregation de-escalation (Bosse & Provoost, 2015), and behaviour change (Klein et al., 2017). Though, the detailed processes of integrating these models into agent technology were not fully developed as those models were used as a design principle. It is essential to remark that such computational cognitive models can be considered as one of the fundamental elements to be integrated into companion robots. This is crucial as the new trend of robot applications are towards designing robots with deep understanding of human cognitive processes as it plays beneficial roles in terms of providing assistance in a knowledgeable and sociable manner (Matarić & Scassellati, 2016; Breazeal, 2017; Augello et al., 2018; Cominelli, Mazzei, & De Rossi, 2018)

In light of the above insights on the importance of human functioning models, this study aims at developing an ambient agent model that can be integrated into a robot. To attain this, an ambient agent model of cognitive load and reading performance was chosen to be developed and integrated into a reading companion robot, aims to support readers in an informed way during their reading process. The choice was made due to the reading task is always hampered with the adverse effects of cognitive load, especially when the reading process is assigned to solve complicated task or to seek for new knowledge (i.e., learning occurrences) (Gillmor et al., 2015; Mills et al., 2017). Due to the intense load readers or learners have experienced while solving difficult reading tasks, they may expose to the unwanted effects such as lack of motivation, mental or physical exhaustion (Paas, Tuovinen, van Merriënboer, & Aubteen Darabi, 2005; Schnotz, Fries, & Horz, 2009; Lee, 2014; Gillmor et al., 2015; van Cutsem et al., 2017; Baars, Wijnia, & Paas, 2017). As a result, such negative ramifications contribute largely to the possibility of reading disengagement, that later impedes reading performance (Choi et al., 2014). Despite it is imperative to understand the cognitive load processes, not much attention has been paid towards modelling the dynamics of cognitive load and its impact on reading performance (e.g., in the form of ambient agent model). However, two notable models of cognitive load have been developed by Sawicka (2008) and Choi et al. (2014). These models were developed to provide conceptual insights on the basic mechanism behind cognitive load based on Cognitive Load Theory (CLT). Nevertheless, it is not applicable to be implemented in any digital systems, unless those models were reconstructed and formalized with additional important cognitive components such as persistence (Schnotz, Fries, & Horz, 2009; Liu, Raker, & Lewis, 2018) reading performance (Choi *et al*., 2014), motivation (Vandewaetere & Clarebout, 2013; Woo, 2014), and exhaustion (Jaber, Givi, & Neumann, 2013; Hanken, Eling, & Hildebrandt, 2015). By having these additional cognitive constructs, it can facilitate the development of a reading companion robot that allows reading processes. In addition, those cognitive models are yet to be validated through any empirical study.

Based on previous explanations, this study aims at developing an ambient agent model that explains the integration of an ambient agent model (the human functioning model of cognitive load and reading performance) within a reading companion robot. This integration allows a companion robot to support readers in a human-like way during demanding reading tasks.

1.3 Research Questions

The main question needs to be answered is how ambient agent models of human's physical and cognitive processes can be integrated into companion robots to provide intelligent support for readers in an informed manner during reading processes. To answer this question, the following sub-questions are formulated.

i. What are the psycho-cognitive factors and their relationship to develop a computational cognitive agent model of cognitive load and reading performance?
ii. How to develop an ambient agent model for cognitive load and reading performance based on the developed cognitive agent model?

iii. Can the developed ambient agent model be integrated into a reading companion robot?
iv. What will be the performance of the implementation of the ambient agent model within a reading companion robot context?

1.4 Research Objectives

The major aim of this study is to develop an ambient agent model that can be integrated into companion robots to assist human in reading tasks. To attain this aim, the following sub-objectives need to be accomplished.

i. To develop a computational cognitive agent model based on analysed psycho-cognitive factors and its relationships of cognitive load and reading performance.
ii. To develop an ambient agent model for cognitive load and reading performance based on the developed cognitive agent model.

iii. To develop integration algorithms to integrate the developed ambient agent model into a reading companion robot.
iv. To evaluate the ambient agent model and its implementation within a reading companion robot context.

1.5 Scope of the Study

This study intends to develop an ambient agent model of human's physical and cognitive processes that can be used as a fundamental component for smart reading companion robots. This ambient agent model focuses on analysing the impact of cognitive load and its ramifications like *motivation*, *persistence*, and *exhaustion* on reading performance. Furthermore, this study uses *Network Oriented Modelling* technique based on Temporal Causal Networks approach. Besides, the ambient agent framework (i.e., *Belief-Desire-Intention*) has been used to develop an ambient agent model that can be used to support readers during their reading processes. Moreover, this study also focused on designing a reading companion robot that resembles a reading table lamp.

As for the evaluation purposes, this study recruited a number of undergraduate (Bachelor of Science (Information Technology) with Honours) students from School of Computing at Universiti Utara Malaysia as participants to validate the developed reading companion robot. This group of students had been identified to have difficulties in solving assignments for Data Structure and Algorithm Analysis subject. Prior to that, the ambient agent model was evaluated using mathematical analysis and logical verification approaches. Also, human-based experiments were conducted to evaluate to implementation of the proposed model in a reading companion robot.

1.6 Significance of the Study

This study introduces an integrated ambient agent model of cognitive load and reading performance within a reading companion robot context to support readers by making their reading process seamless and meaningful. To this end, the significance of this study could be viewed from two perspectives; theoretical and practical contributions.

1.6.1 Theoretical Contributions

The theoretical contributions of this study can be seen in four substantial components. The first theoretical contribution is determining the essential factors that explain the temporal dynamics of cognitive load and reading performance related to their relationships. Later, these constructs can be used to find support factors to reduce the negative ramifications of cognitive load. The second theoretical contribution is the cognitive agent model of cognitive load and reading performance. This agent-based model simulates the dynamics of cognitive load when a reader is performing demanding reading tasks over time. The simulated results can be used by psychologists or cognitive scientists to get deeper insights related to the dynamics and mechanics of cognitive load and its impact on reading performance.

The third contribution of this study is the integration mechanism of an ambient agent model of cognitive load and reading performance into an agent / robotic technology as the proposed model is capable to provide a computational understanding and mechanism about support and interventions. Therefore, this model could be extended as a basis to assist readers during demanding reading tasks. Lastly, the final theoretical contribution of this study is the general model design that integrates the ambient agent model of cognitive load and reading performance into a reading companion robot. Therefore, this model can be used as a design blueprint for other technical endeavours in designing a smart ambient intelligent agent/robotic system based on human functioning models.

1.6.2 Practical Contributions

From the practical perspectives, this study provides implementation guidelines for a companion robot, named as IQRA'. It resembles a stationary reading table lamp. Within IQRA', it provides how the developed ambient agent model can be integrated as an intelligent software agent. In other words, IQRA' robot provides a practical example on how ambient agent models based on human functioning models can be integrated into any intelligent digital artefacts. Furthermore, this practical contribution leverages the understanding in designing robots that demonstrates social intelligence abilities as IQRA' interacts with humans through a set of social-like interactions rather than typical human-robot interactions via control buttons.

1.7 Organization of the Study

This study is structured into seven chapters as follows.

Chapter One: Introduction

This chapter introduces the necessary understanding and fundamental concepts that were used in the later chapters. It starts with the introduction and problem statement of the study. Later, it discusses the objectives of this study and its significance.

Chapter Two: Literature Review

This chapter explicates the essential components that were reviewed in this study to obtain adequate information related to ambient intelligence, intelligent agent concepts, cognitive load and reading performance, human functioning models, and companion robots.

Chapter Three: Research Methodology

This chapter presents the research methodology steps that were used in the study. Each step in this research methodology provides a scientific way to conduct the study. Three main paradigms were implemented, namely; (1) Design Science Research Process (DSRP), (2) Agent-Based Modelling (ABM), and (3) Ambient Agent Framework (AAF).

Chapter Four: Cognitive Agent Model Development

This chapter discusses the design steps of a cognitive agent model of cognitive load and reading performance. It begins by identifying the cognitive load factors and its interplays. Later, these factors are formalized using a *Network Oriented Modelling* approach for computational simulation purposes. Also, it utilizes a numerical computing environment to simulate the behaviour of the cognitive agent model.

Chapter Five: Ambient Agent Model Development and Robot Design

This chapter presents the design steps of an ambient agent model of cognitive load and reading performance. It identifies the support factors based on the developed cognitive agent model. These factors are implemented within ambient agent framework and formalized using Belief-Desire-Intention and First-Order Predicate Logic (FOPL) approaches. It employs LEADSTO tool for a logical implementation platform to simulate different cases of the developed model. Also, it describes the integration of the ambient agent model into an agent technology via computer simulations. Apart from the ambient agent model development, this chapter presents the design principles for a reading companion robot. It includes concepts about software and hardware components.

Chapter Six: Evaluation

This chapter presents the evaluation stages in this study. It includes verification and validation stages. The verification stage is accomplished through stability analysis (mathematical analysis) and automated trace analysis (logical analysis) to evaluate both the cognitive agent and ambient agent models, whereas validation is conducted through human experiments to evaluate the ambient agent model implementation within a reading companion robot context.

Chapter Seven: Conclusion

This chapter summarizes how this study has achieved its objectives and details about the implication of the study. It also highlights limitations of the study with suggestions on further work that can be extended to improve this study.

1.8 Operational Definitions

Domain Model: Throughout this study, *domain model* term was used in two interpretations. Firstly, it defines as a step in the agent-based methodology that revolves around identifying related factors to conceptualize an agent model. Secondly, it represents a complete human-agent model within an ambient agent framework where the obtained cognitive agent model (for cognitive load and reading performance) is called a domain model within an ambient intelligent agent framework.

Reading Task: It is a task that requires serious reading to acquire new information or to solve complex tasks. For instance, reading technical materials to solve a difficult mathematical task.

Reading Performance: Reading performance refers to what extend a reader is engaged in a reading task to achieve his/her goal. It is important to relate that it does not refer to reading/ learning outcomes, but more to ensure the continuity of reading processes despite of the feeling of imposed demands.

1.9 Summary

This chapter presented the motivations behind this study where the main problem statement was stated, and objectives of the study were laid. It also pinpointed the significance of the study. Moreover, at the introductory part, the detailed explanations were described to consolidate the aims of conducting this study. Next chapter covers literature reviews within the domain of this study.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter discusses related work and foundations of the study. It begins with a brief introduction about the core concept of an agent technology in Section 2.2. Following this, important concepts in agent technology and related building blocks for agent-based modelling were analysed. Section 2.3 discusses the initial components of the agent architecture especially ambient agent architecture and agent applications. Later, section 2.4 provides extensive reviews about human functioning models and computational modelling of cognitive processes. Section 2.5 provides details on the evaluation methods of human functioning models. Next, the underlying theoretical and practical concepts in companion robots, human robot interaction, embodiment of robots, and detailed review about applications of robots were made as in Section 2.6. Later, mechanical constructs in the domain of reading / learning and types of reading were discussed. These principles provide important insights about the domain as explained in Section 2.7. Section 2.8 presents the concepts of cognitive load and reading performance. It covers an extensive review related to cognitive load models and theories. Both Section 2.9 and 2.10 focus on the measurement methods in cognitive load and the essential constructs of cognitive load for ambient agent model development. Finally, Section 2.11 concludes this chapter.

2.2 Ambient Intelligence (AmI)

The advancement of making smarter machines with ambient intelligence requires multi-disciplinary approaches. Thus, it permits a wide-range of research perspective to have an important beneficial impact into society. The ambient intelligent system requires cohesive integration between smart sensors or devices and its environment to allow an immersive and subtle triadic human-machine-environment interaction (Augusto & McCullagh, 2007). For instances, smart home applications to support modern lifestyle (Makonin, Bartram, & Popowich, 2013), health related applications to increase the efficiency of healthcare services by proactively monitoring patients' health and progress in their rooms (Martín, Alcarria, Sánchez-Picot, & Robles, 2015; Korzun, 2017), education services where universities and higher institutions use smart card technology to permit access to computing and library facilities, car parks, dining halls and lecture rooms (Augusto & McCullagh, 2007), and many other applications in various domain such as public transportation, surveillance, and emergency services.

In many ways, the AmI concept is broadly defined as visioning ideas to have intelligent systems and smart environments with adaptive and proactive analytical capabilities (Streitz, 2017). Hence, the landscape of ambient intelligence has been shifted by incorporating human knowledge models to meet the aforementioned characteristics (Treur, 2016b). This kind of human-environment centric covers the analysis of human's cognitive state and dynamics in relation to existing application. Therefore, these intelligent systems will have the computational capability to analysis possible actions and support humans in a timely fashion (Truer, 2016b).

For comprehensive insights on ambient intelligence, Chong and Mastrogiovanni (2011) summarized different essential components of AmI elements related to the information flow between components. Figure 2.1 depicts these components with the flow of their information.

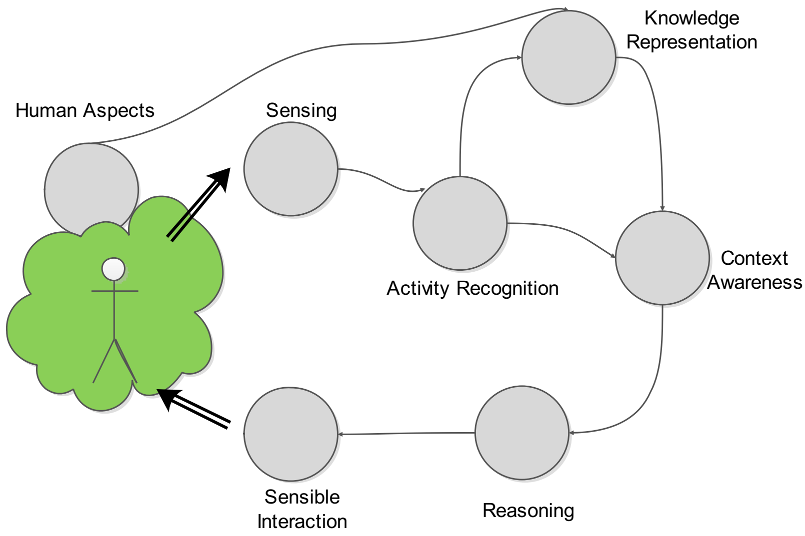

Figure 2.1. Information Flow within Ambience Intelligence Components (adopted from Chong and Mastrogiovanni (2011))

From Figure 2.1, the human aspects of AmI capabilities aim to understand human actions, mood, desires, and feelings. Sensors (or data capturing devices) provide an essential input element to ensure seamless data flow for any AmI systems. For example, the ambient intelligent systems sense users' information based on their activities (activity recognition) and represent this information (knowledge representation) to assess the situation (context awareness). The analysed results will be used as a basis to reason and decide optimal solutions or actions based on the evaluated situations.

Furthermore, within AmI system sensors and devices should be modelled as intelligent, autonomous artefacts rather than only passive information sources (Bohn, Coroamă, Langheinrich, Mattern, & Rohs, 2005; Bosse & Sharpanskykh, 2010). Hence, the implementation of an agent paradigm offers a smart reasoning mechanism for intelligent ambient devices, such as autonomous decision making processes with the environment by the mean of communication, observation and actions (Wooldridge, 2009). Therefore, this study has made use of an agent paradigm in ambient intelligence as a foundation to design an intelligent ambient agent model for cognitive load and reading performance. This model is incorporated within a reading companion robot as a demonstrable artefact for evaluation purposes.

2.3 Concepts in Agents

The earliest agent definition was described by Russell and Norvig (1995) where an agent is a computer system that is situated in some environment and capable of performing autonomous actions in this environment in order to meet its ultimate design goal. Similarly, Wooldridge and Jennings (1995) have explicated agents as software or hardware entities able to perform their own predefined objectives based on its perception of its environment. These concepts are shown in Figure 2.2. It shows an agent perceives its environment using sensors and responds or performs actions using actuators to achieve its goal.

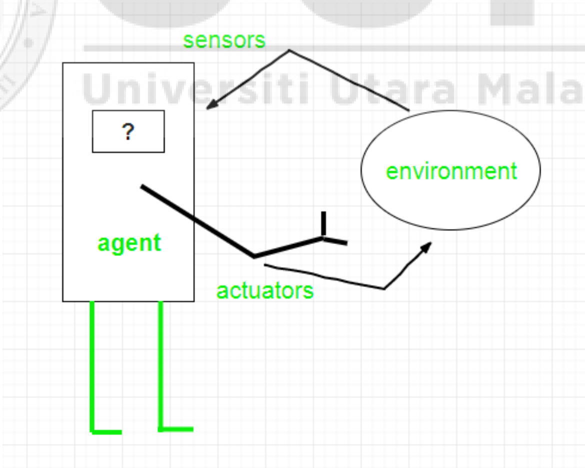

Figure 2.2. The Robot Agent Interacting with Its Environment

Furthermore, for an agent to function in its environment it should depend on some characteristics. These characteristics are; (1) its abilities which are the primitive actions it is capable of carrying out, (2) goals which are the objectives it tries to achieve, (3) prior knowledge about the agent itself and its environment, and (4) history which composed of observation and past experiences of the interaction. Thus, by coupling the interplay between perception, reasoning, and acting, it comprises the main functionality of an agent (Poole & Mackworth, 2010). The four agent's characteristics are depicted in Figure 2.3.

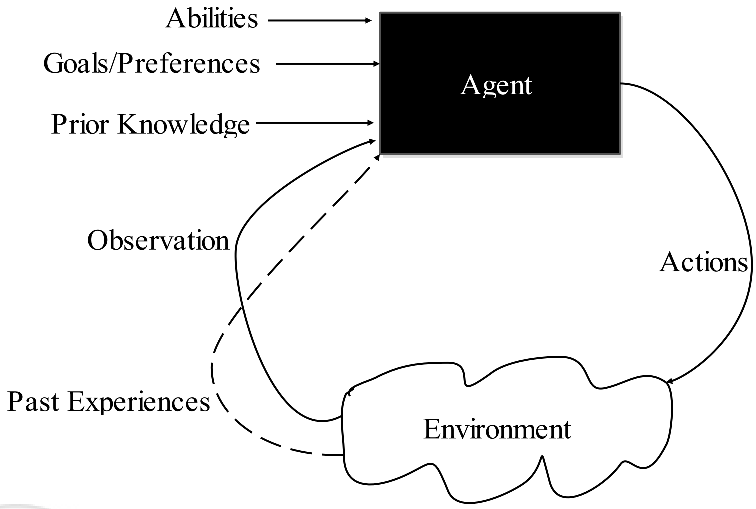

Figure 2.3. An Agent and Its Interaction within Situated Environment

Apart from the aforementioned attributes of agents, previous research works have discussed that agents could be encapsulated with several different attributes and each type of an agent might have different attributes to function in its environment in an intelligent and sophisticated manner (Mostafa, Ahmad, Mustapha, & Mohammed, 2017). These properties are mainly categorised based on the notion of agency, either weak and strong notions (Brazier, Jonker, & Treur, 2000; Wooldridge, 2009). The weak notion of an agent covers four different properties, namely; autonomy, pro-activeness, reactivity, and social abilities while the strong notion encompasses adaptivity, pro-creativity, and intentionality. It is interesting to mention that these attributes acquire their importance based on the specifications of the research domain (Wooldridge, 2009). Table 2.1 discusses the concepts of agent's attributes based on the weak and strong notions of an agent.

Table 2.1

Weak and Strong Notions of an Agent

	Concept	Description
Weak Notion	*autonomy*	Agent functionality that is not directly controlled by humans or another agent.
	pro-activeness	Agent's ability to show goal-directed behaviour in order to satisfy its design objectives.
	reactivity	Agent's ability to interact with its environment by perception and respond in a timely fashion to changes that occur in it to meet its design objectives.
	sociability	Agent's ability to interact with humans or other agents in a social act to attain its predefined objectives.
Strong Notion	*adaptivity*	The behaviour of an agent that learns and improves with experience.
	pro-creativity	The agent behaviour that satisfies certain conditions and its chance to survive is relying on a fitness function.
	intentionality	The mentalistic properties such as knowledge, belief, desire, intention, goal, and commitment.

From software engineering perspectives, these agent's attributes can be extended and concretized by associating further attributes with agents such as situatedness or embeddedness (i.e., an agent interacts directly in a concrete and sociotechnical environment and not only in an abstract model of this environment), benevolence (i.e., an agent does not deliberately act contrary to the interests of a human user), and persistency (i.e., an agent does not simply implement a one-time computation, but acts over a longer period of time) (Weiss, Braubach, & Giorgini, 2010). It is necessary to remark that it is very uncommon to consider all the attributes in an agent due to the complexity of such consideration (Mostafa et al., 2017). Hence, this study aims at incorporating the weak notion of an agent in addition to mentalistic attributes in designing a reading companion robot that can assists in cognitively demanding tasks.

2.3.1 Agent Based Modelling

In the field of agent-based systems, an Agent-Based Modelling (ABM) concept is coined as a method of representing complex and emergent phenomena of autonomous agents to simulate possible outcomes of inter-related agents based on its behaviours and interactions. The simulation results will provide a basic guideline towards a better decision making (Nicholls, Amelung, & Student, 2017). Moreover, it refers to a category of computational models invoking the dynamic actions, reactions and intercommunication protocols among the agents in a shared environment, in order to evaluate their design and performance and derive insights on their emerging behaviour and properties (Abar, Theodoropoulos, Lemarinier, & O'Hare, 2017). ABM is outperforms traditional modelling techniques due to a number of several characteristics (Bazghandi, 2012). These characteristics are; (1) ability to captures emergent phenomena that imperative to model unpredictable and complex behaviours, (2) ability to model complex systems and present them in a natural descriptions where the model seems closer to reality, and (3) flexible in terms of the ability to modify or add more agents to the agent-based model or even to tune the complexity of the agents such as behaviour, degree of rationality, ability to learn and evolve, and rules of interactions. Moreover, ABM is considered as low-cost and time saving approaches for computational efforts. Also, it has a computational property to simulate population of artificial communities through its interaction in virtual environments (An, Mi, Dutta-Moscato, & Vodovotz, 2009). Due to these advantages, ABM has become one of the important modelling methods for *in silico* experimentations where a large number of virtual populations have become easy to be generated and simulated as this is not the case for *in vivo* and *in vitro* experimentations (Dutta-Moscato et al., 2014). Thus, the ABM concepts have attracted different fields such as physics, biology, chemistry, economics, and social sciences (Piacenza, Richards, & Heppell, 2017; Rogers & Cegielski, 2017; Wang, Zhang, & Zeng, 2017; Zhang, Igoshin, Cotter, & Shimkets, 2018).

Another key feature of ABM is the ability to perform reasoning, particularly for human behaviour models. This approach has been successfully implemented to model complex cognitive and physical states of human. Later, this could be translated into a set of mechanisms to analyse and predict future behaviours through a set of reasoning processes. For example, reasoning about frustration and misbehaviour of stranded passengers (Medeiros & van der Wal, 2017) and analysing human behaviour in promoting physical activities (Klein, Manzoor, & Mollee, 2017). It is important to mention that the agent with such capability is considered as an ambient agent model (Bosse, Hoogendoorn, Klein, & Treur, 2011). There are two prominent reasoning approaches have been widely used within an ambient agent-based model for human-like analysis manner. First, the basic reasoning approaches to reason about human behaviours when adequate information is available (forward and backward reasoning techniques). Second, the reasoning approach based on incomplete information where non-monotonic logic techniques are applied to formalize reasoning processes that deal with multiple possible outcomes. This approach is essential to model different possibilities of interpretation (Bosse et al., 2012). An example of reasoning with ambient agent applications can be seen in (Bosse, Duell, Memon, Treur, & van der Wal, 2015) in which an intelligent ambient agent model was developed to analyse and predict emotion contagion within a group of people. Based on the aforementioned concept, this study utilizes the first method of reasoning to predict reader's cognitive and physical states during cognitively demanding tasks. Table 2.2 summarizes a number of examples on the implementation of ABM in different domains.

Table 2.2

Examples of ABM Applications

No.	Author	Year	Description	Domain
1	Yang and Diez-Roux	2013	Modelling active travelling to school among children	Transportation
2	Giachetti, Marcelli, Cifuentes, and Rojas	2013	Modelling best design decisions in human-robot team performance.	Military
3	Kruzikas et al.	2014	Modelling region population, disease burden, and health care infrastructure to predict investment decisions effects on population health and health care costs	Healthcare
4	Crooks and Hailegiorgis	2014	Modelling the spreading of cholera outbreak in the Dadaab refugee camp in Kenya	Healthcare
5	Briggs and Kennedy	2016	Virtual shooting environment for training purposes	Safety/ Security
6	Haer, Botzen, and Aerts	2016	Estimation the effects of flood risk communication strategies to increase people's awareness	Crisis management
7	Hsu, Weng, Cui, and Rand	2016	Modelling the complexity of project team member selection and team performance	Economic
8	Cornelius, Lynch, and Gore	2017	Simulation of age-crime occurrence relationships for better crime policies	Criminology
9	Chesney, Gold, and Trautrims	2017	Analysis the effects of shadow account for decision support systems	Economic
10	Bongiorno, Miccichè, and Mantegna	2017	Dynamics in relationship of aircraft and air traffic controller to detect decision conflict	Air traffic management

The details on formal modelling concepts in designing ambient agent-based models are covered in Section 2.4. Next section provides fundamental explanations on agent architectures for decision making processes of an agent.

2.3.2 Agent Architectures

This subsection explores agent architectures that were used to develop agents' applications. The significant role of an agent's architecture is to construct a building block that provides complete understanding on how incoming information to an agent can be used to specify the future states and actions of the agent (Wooldridge, 2009). The agent architecture concept was defined as the "functional brain of an agent that helps in making decisions and gives reasoning ability to solve problems and achieve goals" (Chin, Gan, Alfred Rayner, Anthon Ypatricia, & Lukose, 2014). In general, there are three categories of agent architectures (Chin et al., 2014), namely; (1) classical agent architectures, (2) cognitive agent architecture, and (3) semantic agent architecture. The classical agent architectures involve logic-based, reactive, Belief-Desire-Intention, and hybrid architecture.

The logic-based architecture is considered as the earliest type developed by Newell and Simon (1976). It heavily uses a traditional artificial symbolic approach for reasoning (i.e., symbolic representation). Russell and Norvig (1995) demonstrated the implementation of this architecture by using a vacuum cleaning scenario. However, this architecture has two main pitfalls that make it undesired choice as an agent development platform; (1) the difficulty in transforming complex and dynamic environments into a set of symbolic representations accurately for computational processes, and (2) the transformation of perception input may not be accurate due to faulty sensors or reasoning errors. Contrary, the reactive agent architecture was designed based on stimulus-response manners to overcome the aforementioned issues. The reactive agent architecture is directly mapped to act based on a perceived situation or need from the environment. This perceived situation can be detected using a set of effectors or sensors (perceptual input from the environment). However, Togelius

(2003) has pointed out that this architecture has insufficient information about agent's current state, difficulty to learn, and unable to predict agent's future behaviours. These limitations made it impossible to build task-specific agents which among important design requirements for any autonomous intelligent agents.

To overcome those issues, the layered architecture (hybrid agent architecture) was introduced combining both symbolical and reactive architectures. The hierarchal approach has provided great advantages to rule out issues in those previous architectures. Despite its versatility, its robustness is one of its disadvantages whereas if one of its layers failed therefore the whole system would fail as well. Thus, it is a serious issue to be tackled by an intelligent monolithic system such as an agent.

This specific issue has been solved by introducing the *Belief-Desire-Intention* (BDI) architecture into the reactive agent architecture. Beliefs are the set of information an agent has about the world while desires are the agent's motivation or possible options to carry out the actions, while intentions are the agent's commitments towards its desires and beliefs (Chin et al., 2014). The BDI architecture was made initially based on Bratman's philosophical practical reasoning. Practical reasoning has provided a mechanism to figure out what to do next or the next action for any agent. It also has been defined as:

> *"*Practical reasoning is a matter of weighing conflicting considerations for and against competing options, where the relevant considerations are provided by what the agent desires/values/cares about and what the agent believes*"* (Bratman, 1990).

The BDI architecture is particularly interesting and being widely used as it combines three different components (Wooldridge, 2000), namely; (1) philosophical components based on Theory of Rational Action in Humans, (2) implementation components used to build real-world applications, and (3) logical components for a rational agency and formal logic approach.

The strength of this architecture is the efficient capability of modelling human behaviour, though the initial design of BDI was neither meant to model humans' mind nor to develop sophisticated and intelligent agents that act in similar way of human (Norling, 2009).

Although other agent architectures such as ACT-R and Soar provide alternatives to model the cognitive process within intelligent agents, the BDI architecture has been proven outperforms those two architectures as it is based on *folk psychology*, which means that the core concept of the agent framework can be mapped easily to the human language to describe their reasoning and actions in daily conversation (Norling, 2004). Based on this, BDI can be considered descriptive enough to describe cognitive processes that affecting behaviours, and intuitive enough to be understood by non-computer scientist community (Adam & Gaudou, 2016).

In spite of the fascinating power of BDI in modelling human cognitive processes, it is still inadequate to represent the generic aspects of human behaviours and reasoning due to its high-level abstraction paradigm and assumption (Norling, 2009). Therefore, a cognitive modeller should explicitly code and understand these aspects. However, the introduction of temporality notion (as depicted in Figure 2.4) into current BDI architecture has overcome major weakness of the original BDI architecture (Jonker, Treur, & Wijngaards, 2003), as the formal model only captured the static representations of human behaviours (Rao & Georgeff, 1997).

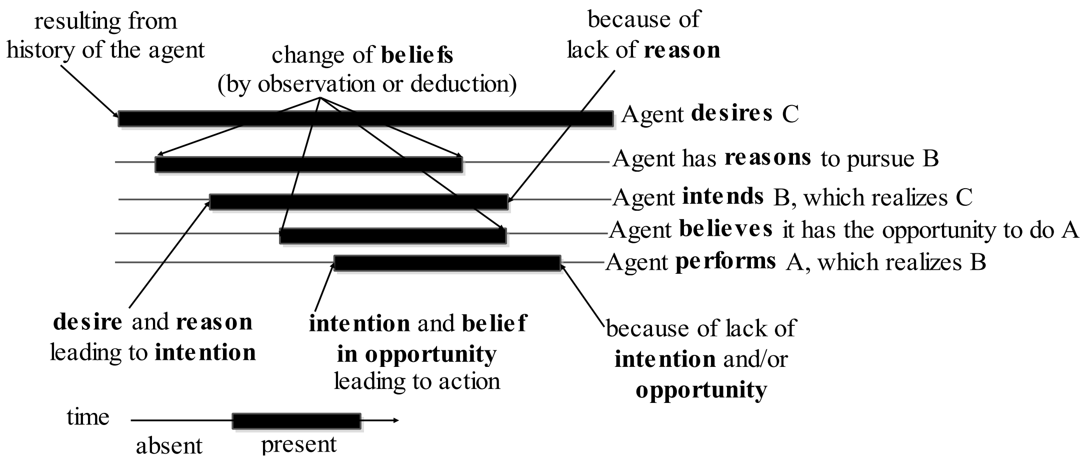

Figure 2.4. BDI Notions Over Time (Jonker et al., 2003)

The integration of temporal properties within BDI architecture allows scientists to model human cognitive behaviours and create human-like or ambient intelligent agents that encapsulate reasoning capabilities to perform informed actions (Bosse, Hoogendoorn, Klein, van Lambalgen, et al., 2011; Bosse, Hoogendoorn, Klein, & Treur, 2011; Bosse, Duell, Memon, Treur, & van der Wal , 2015). Based on those temporal features, this study utilises the temporal notion of BDI agent architecture to develop an ambient agent model of cognitive load and reading performance.

2.4 Human Functioning Models

As the ambient agent models based artefacts are no longer only relying on a reactive approach, but also incorporating knowledge from human-directed sciences such as neuroscience, biomedical science, cognitive science, and physiological and social sciences, thus the obtained knowledge has becoming vital to perform more in-depth human-like analysis for reasoning decisions to take place (Treur, 2018). This human knowledge could cover various concepts such as elderly people, patients depending on regular medicine intake, surveillance, penitentiary care, self-help communities as well as humans in highly demanding tasks such as air traffic controllers, crisis management, warfare officers, and human in space missions (Bosse et al., 2011). This can result in an environment that may more effectively affect the state of humans by undertaking actions in a knowledgeable manner that improve their wellbeing and performance.

Several human functioning models have been developed to understand human cognitive and physical states and incorporated within intelligent artefacts to assist people in human-like manners. For example, model of stressed person in social media context to create virtual friends to alleviate stress (Medeiros & Bosse, 2017), and model of human behaviours to promotes physical activity (Klein, Manzoor, & Mollee, 2017). Sections from 2.4.1 to 2.4.3 discuss the underlying grounded concepts in developing human functioning models using an agent-based modelling approach.

2.4.1 Concepts in Modelling

Within scientific communities, modelling is one of the methods to understand the real-world systems by abstracting the complexity for particular phenomena. Models have always come in various forms such as conceptual models (Tomé Klock et al., 2015), graphical models, statistical models (Freedman, Midthune, Dodd, Carroll, & Kipnis, 2015), logical models (Bouzeghoub & Kedad, 2000), and computational models (Mui, Mohtashemi, & Halberstadt, 2002).

Pertaining to the computational modelling (or agent based modelling), it refers to the process that gives detailed description of a set of processes in a real world to acquire deeper understanding about these processes and to predict the outcomes of the processes by a set of given particular inputs and parameters (Aziz, 2012). Generally, it aims to imitate some important features of the examined system while discarding inessentials and it can be done by using algorithmic descriptions (Sun, 2008). From another perspective, a computational model also being used to model how system and its properties behaves over the time (Ellner & Guckenheimer, 2006). Also, this approach utilizes grounded theories (i.e., data is not necessarily available to develop any model). For example, an emotional concept model (Sun, 2008), a decision making model (Hoogendoorn, Merk, & Treur, 2010), a driver's behaviour model (Bosse et al., 2011) and a model of physical and mental health (Klein et al., 2015).

Therefore, by using a computational modelling approach to model dynamic phenomena seems to be the most remarkable technique in several aspects as it offers expressive power and flexibility that may be insignificant in other approaches (Sun, 2008). Thus, it allows scientists to explore complex relationships that could not be identified in traditional experimental methods or to make approximations that cannot be done easily by estimating patterns from the existing datasets (Sawicka, 2008). Also, computational models are capable to provide a set of facilities to capture certain observed areas, which these models deliver means of risk-free exploration in complex, time-consuming, costly, critical, or seldom situations. For instance, in a neuroscience domain, theoretical neuroscientists develop computational models to understand the dynamics of cognition and neural processing to clearly know when humans act, perceive, learn, think or remember certain tasks. Despite of the state-of-the art and breakthrough in powerful imagining machines and software, these devices are still not completely advanced enough to fully understand complex interactions between neurons in our brain (Ellner & Guckenheimer, 2006). As a result, using a computational model is considered as a new way to investigate external and internal processes within brain activities.

From human behaviour analysis paradigms, computational models also reduce "Hawthorne Effect" that may affects experiment settings as it is obvious when people realize they are being observed, they will change their behaviours (Rosenthal, 1966). Therefore, it may become difficult to preserve the same condition for each different setting during the experiments. Also, computational models can be used as a hypothesis about an observed system by simulating and replicating possible conditions and to see the likelihood of pre-defined hypothesis testing. Thus, if a hypothesis fails, it can be neglected without doing more of unnecessary real world experimentations (Farrell & Lewandowsky, 2010). Another advantage of using computational models is to leverage the size of an observed system. For example, for experiments that are not easily to be conducted conventionally, computational models can be used to generate smaller sized experiments for the large-sized assumptions (i.e., emergent and complex behaviours) (Eldabi & Young, 2007). From Artificial Intelligence perspectives, computational models play important roles as a basic mechanism to provide intelligent reasoning and analysis. For instance, an intelligent room development (Macindoe & Maher, 2005), an intelligent agent for future human life-like interaction (Alidoust & Rouhani, 2015), an intelligent avatar for aggregation de-escalation (Bosse & Provoost, 2015), and a coaching system for behaviour change (Klein et al., 2017). From these foundations, this study utilizes an agent-based modelling as a core component in developing a reading companion robot to support readers when they encounter cognitive overload.

2.4.2 Theoretical and Practical Computational Models

In general, computational models can be categorized to serve two functions; theoretical understanding and practical application. The theoretical standpoints aim to understand the underlying process of an actual system, while a practical perspective uses a model to predict the actual system through a set of feasible actions (Ellner & Guckenheimer, 2006; Weinhardt & Vancouver, 2012; Mc Auley & Mooney, 2018). For both perspectives, dynamic mathematical equations are usually used to represent theoretical models, and those equations are yet simple enough for scientists to comprehend the underlying process. These models should be simple (KISS- "Keep It Simple Stupid" principle) and expressive enough otherwise it is useless to replace an observed system with a complex model that difficult to comprehend when it has not increased our deeper understanding of the observed domain. This idea must be consistent to the Occam's Razor Law of Parsimony concept, where if presented with the competing hypotheses to solve a problem, one should select the solution with the fewest assumptions. On the other hand, practical models generally move out simplicity to provide more comprehensive and precise predictions for an observed system. Therefore, practical models are frequently very complex and only developed for computer simulations objectives (Ellner & Guckenheimer, 2006; Hannon & Ruth, 2014). In relation to this, the numerical accuracy is essential for practical, whereas this is not the case for theoretical models. Hence, the circumstances of the processes can be omitted if it has less influence in determining a better predictive accuracy. However, in the case of theoretical models, the details of processes can be excluded if they are not related to address essential theoretical groundings (Aziz, 2012; Hannon & Ruth, 2014).

2.4.3 Computational Models in Psychology

Psychology is the domain of studying human mind and behaviour in both fields; practical and academic (Farrell & Lewandowsky, 2010). Research in psychology aims to know and explain the theoretical structure of emotion, behaviour, and thought. Moreover, it has ascertained that most of human psychological processes are too complex to be understood only based on behaviour observation, especially when basis theories are not fully comprehended in explaining observed conditions (Scassellati, 2002; Das, Kamruzzaman, & Karmakar, 2018; Pandey & Tiwari, 2018). Besides, since the process of human mind is complex and it has great influence in behavioural flexibility, computational modelling is more favourable to illustrate the processes and its interactions (Farrell & Lewandowsky, 2010). As computational modelling can further the details level of a process and increase the scale of input-output interactions, it is very significant to explain the level of cognitive functions (Gagliardi, 2007).

Computational models are extensively used as in-silico experimental tools to investigate human behaviours and cognitive functions such as attention, processing speed, learning and memory, and decision making (Kirou, Ruszczycki, Walser, & Johnson, 2008; Sharpanskykh & Treur, 2010b; Duell & Treur, 2012; Kumar, Prakash, & Dutt, 2014; Pontier, van Gelder, & de Vries, 2013; Zhao et al., 2015). Results from the simulations are used to justify that the models offer good explanations of the cognitive mechanisms relevant to the corresponding domains of interest. In psychology, cognitive modelling is one of the aspects that leverages formal/computational models to study human mind and its mechanism (Bosse, 2005). In (Detje, Dorner, & Schaub, 2003), cognitive modelling is described as follows:

> *"Cognitive modelling is a method to study the human mind. Cognitive Modellers try to explain the structure and the processes of the human mind by building them. As this, Cognitive Modelling is "Synthetic Psychology". A model of human cognition should mirror human mental activities, human errors, slips and mistakes. Cognitive Modellers try to understand how the human memory works, how the human memory is structured to reflect reality, how the human memory is used for the organization of behaviour. The scope of Cognitive Modelling is widened beyond cognition to more general and more complicated forms of psychological processes*

which include social, emotional and motivational factors" (Detje et al., 2003)

From these foundations, this study utilizes a computational modelling approach to model the dynamic cognitive process of readers while performing demanding tasks. Table 2.3 explains several examples of various computational models and its techniques used in developing them as well.

Table 2.3

A Summary of Computational Models Techniques

No.	Author	Year	Title	Techniques
1	Bosse, Memon and Treur	2011	A Recursive BDI Agent Model for Theory of Mind and Its Applications	First Order Logic
2	Soleimani and Kobti	2012	A Mood Driven Computational Model for Gross Emotion Regulation Process Paradigm	Differential Equation
3	Naze and Treur	2012	A computational model for development of post-traumatic stress disorders by Hebbian learning	First Order Logic
4	Both, Hoogendoorn, Van der Mee, Treur, and de Vos	2012	An intelligent agent model with awareness of workflow progress	First Order Logic
5	Steephen	2013	Hed: A computational model of affective adaptation and emotion dynamics	Differential Equation
6	Mollee & van der Wal	2013	A computational agent model of Influences on physical activity based on the social cognitive theory	Differential Equation

Table 2.3 continued.

7	Abro, Klein, Manzoor, Tabatabaei, and Treur	2014	A Computational Model of the Relation between Regulation of Negative Emotions and Mood	Differential Equation
8	Bosse, Duell, Memon, Treur, and van der Wal	2015	Agent-Based Modelling of Emotion Contagion in Groups	Differential Equation
9	Goedschalk, Treur, & Verwolf	2017	A Network-Oriented Modelling Approach to Voting Behaviour During the 2016 US Presidential Election	Differential Equation
10	Bosse, Duell, Memon, Treur, & van der Wal	2017	Computational model-based design of leadership support based on situational leadership theory	First Order Logic

2.5 Evaluation Methods of Human Functioning Models

Modelling human functioning has kept up playing remarkable roles in creating systems that possess human-like understanding. Moreover, a key success of these models is ensuring its successful development. Hence, evaluation process of developing human functioning models has a major impact in proving the model is developed in an appropriate manner. It means the model process and its predictions are rigor and credible significantly. To evaluate human functioning models, a range of activities are required to ensure the reliability and accuracy of the developed models. These activities include verification and validation. Next subsections discuss the processes that cover the underlying concepts of verification and validation.

2.5.1 Verification

In human functioning modelling (computational modelling) evaluation, verification refers to the processes that prove the developed computational model is implemented and working in a right manner (Treur, 2016d). Basically, it deals with checking the equations of the developed model to investigate the structural and theoretical correctness of the model which involves deductive arguments on the model logical statements (da Silva & De Melo, 2013). Regarding this, many mathematical techniques have been employed to investigate the structural and theoretical correctness of computational models. For example, stability analysis (mathematical proofing to determine equilibrium points) (Bosse et al., 2009), sensitivity analysis (i.e., to make sure that model's parameters are sufficiently accurate to ensure the output of the model remains predictable) (David, 2013), and Routh–Hurwitz stability criterion (Gbenga, 2012). However, in recent years, a great attention has been paid to utilize stability analysis (or equilibrium points) in verifying agent-based models (or human functioning models). For example, modelling emotion contagion in groups (Bosse et al., 2015), and a model for the dynamics in social interaction (i.e., homophily principle) (Treur, 2017b). Moreover, rich literature of mathematical verification using stability analysis can be found in Treur (2016d). Therefore, this study followed-up the success of using stability analysis to verify the proposed cognitive agent model of cognitive load and reading performance.

2.5.2 Validation

On the other hand, validation process is an essential part to ensure that the developed model has been made in relation to the real-world applications. It is always concerns to build the right model (Anderson et al., 2007). In a bid to address human functioning models' validation, previous research studies have employed several methods to validate computational models. For example, conceptual or theoretical validation (experts are involved to determine how the constructed model based on fundamental data is accurate in characterizing the real-world problems), cross-model validation (refers to the comparison between different models to determine their validity), external validation (refers to external experiments against real-world where humans are mainly involved), data validation (refers to the accuracy of actual and generated data (i.e. real world and computer data)), internal validation (refers to the validity of the model based on computer simulations) (Bharathy & Silverman, 2010). With regard to internal validation, a temporal trace language (TTL) are used to prove the model indeed generates results that exactly observed in psychological literatures, where a set of properties should be identified from related empirical studies (Bosse et al., 2009). While, external validity is conducted via human experiment testing (variance analysis) to validate the support effect of the developed model in terms of its ability to reason and provide intended support within a reading companion robot context. A detailed process of human experiment is provided in Section 3.7.2. Furthermore, examples of such studies that applied internal and external validity can be seen in (Hoogendoorn, Memon, Treur, & Umair, 2010; M. Klein, Mogles, & van Wissen, 2011; Treur, 2011).

2.6 Companion Robots

In recent years, designers and scientists are started to be fascinated with the use of robots to augment humans' abilities. They are widely studied and explicated in the last decade as utmost devices that can provide aid for humans. For instance, numerous numbers of robots' applications assist people (assistive robot) and make solutions for particular challenges they might encounter such as autism disorders (Shamsuddin et al., 2012a, 2012b; Hashim et al., 2014), and physical impairment (Kwakkel, Kollen, & Krebs, 2007; Lo et al., 2010; Mast et al., 2015). Similarly, robots' applications have been extensively deployed in various domains such as healthcare (Chang & Šabanović, 2015), education (Westlund & Breazeal, 2015), edutainment (Takase, Botzheim, Kubota, Takesue, & Hashimoto, 2016), industry (Aryania, Daniel, Thomessen, & Sziebig, 2012), and even in military to provide flawless aid for soldiers (Kumar, Verma, Singh, & Patel, 2017).

In the beginning, assistive robots were developed only to assist people with physical disabilities. These assistive robots have been designed and applied in a range of environments such as school, home, and hospital where these robots were physically interacted with humans (Feil-Seifer & Mataric, 2005). Examples of applied physically assistive robots are rehabilitations robots (Burgar, Lum, Shor, & van der Loos, 2000; Dubowsky et al., 2000; Mahoney, van Der Loos, Lum, & Burgar, 2003), wheelchair robots and other mobility aids (Simpson & Levine, 1997; Aigner & McCarragher, 1999; Glover, 2003; Yanco, 2002), educational robots (Kanda, Hirano, Eaton, & Ishiguro, 2003), manipulator arms for the physically disabilities (Kawamura, Bagchi, Iskarous, & Bishay, 1995; Hans, Graf, & Schraft, 2002; Giménez, Balaguer, Sabatini, & Genovese, 2003) and companion robots (Plaisant et al., 2000; Roy et al., 2000; Wada, Shibata, Saito, & Tanie, 2002).

Later, with the advancement in the field of robotics technology, new paradigms of robots have been initiated to serve their intended objectives through human-like social interactions. For example, social robots have introduced where the communication between human and robot has achieved in social manners (Breazeal, 2003). There are four groups of social robots based on their interaction mechanism with human. These are; (1) socially evocative (these kind of robot is solely anthropomorphize robot which interactions happen due to the anthropomorphize shape), (2) socially interface (these kind of robot use human-like social cues to naturalize and familiarize the interaction such as a museum tour guide), (3) socially receptive (advanced robots) that can learn from the interaction with humans but not proactively engaging with people, and (4) a sociable robot that can interact with human in social manners and proactively engaging with people.

Social robots have received great attention from roboticists around the globe as this piece of technological advancements have opened-up a new way to support humans in a social manner. This is one of the requirements needed to allow greater understanding about the field of human-robot interaction (David Feil-Seifer & Mataric, 2011; Gordon & Breazeal, 2017). For example, Matarić (2014) described that socially assistive robots (SAR) is a new subfield of robotics that links together human-robot interaction, social robotics and service robotics. This concept also emphasized the main concern in SAR to create machines capable of assisting users, typically in healthcare and education context, through social interaction (Matarić, 2014).

With the rapid growth in robotics, socially assistive robots vision has been shifted drastically to create robots that can be used in home to complement the efforts of human expertise such as therapist, doctors, and teachers labelled as companion robots (Short & Mataric´, 2017) like keep users company (Johal, 2015). There are two essential challenges in designing companion robots. First, the embedment of social competences is a must in perceiving, reasoning, and acting during their interaction with humans. Second, the acceptance of these robots where extended factors such as trust, legitimacy, and credibility are very important to be incorporated (Johal, 2015; Ullman & Malle, 2017). Hence, to design and create a companion robot that serves users in friendly and social manners is far from easy task and required special attention to integrate the social ability constructs.

2.6.1 Human-Robot Interaction (HRI)

In human-robot interaction, two different views have been studies to understand the communication processes between the two computational entities (Breazeal, Dautenhahn, & Kanda, 2016). The first view relates to the autonomous robots, as they are normally viewed as tools that humans use to perform critical or hazardous tasks in remote environments such as sweeping minefields, inspecting oil wells, and mapping mines. In dramatic contrast, the second view relates to the companion robots, as they are mainly designed to interact and engage people in interpersonal matter, usually as "friends" to attain the needed outcomes in diverse domain such as education, therapy, or task-related goal. The companion robotic domains have opened-up new challenges in studying human-robot interaction. Dautenhahn has pioneered a ground breaking work by analysing social intelligence and relationships between human and robots (Dautenhahn, 1995, 1997). Also, the field of HRI was deeply investigated after the definition of social (or sociable) robots by Breazeal (2004). She defines "sociable robots" as socially participative "creatures" with their own internal-goals and motivations. These robots will pro-actively engage people in a social manner not only to benefit the person (e.g., to help perform a task, to facilitate interaction with the robot) but also to benefit itself (e.g., to promote its survival, to improve its own performance, and to learn from the human).

An essential challenge in human robot interaction (i.e., related to companion robots) is to maintain the interaction between human and robots to produce enjoyable, efficient, natural, and meaningful interaction (Breazeal, Dautenhahn, & Kanda, 2016). The reason is because the main goal of these robots is to provide intelligent support in a social manner and this cannot be achieved without involving fluid social interaction. The interaction always occurs via non-verbal and verbal channels (Bicho, Louro, &

Erlhagen, 2010). The two forms of communications are playing an essential role in increasing the performance of a task while both of human and robot are collaborating as a team in achieving a specific task (Bicho et al., 2010). In Breazeal, Kidd, Thomaz, Hoffman, and Berlin (2005), they have confirmed the positive effect of non-verbal behaviours in human-robot teamwork and its relationships with task performance errors reduction in performing tasks. Therefore, it gives a limelight to address verbal and non-verbal cues extraction when designing a robot.

In addition, to design an assistive companion robot that is able to interact with its users effectively; a number of specific factors need to be considered. For example, these are; robot-gender, subject-gender, interpersonal distance, touch, and perceive autonomy of the robot (Siegel, 2008). The effects of the aforementioned factors have been studied in people's personal spaces (Takayama & Pantofaru, 2009), gender of a robot (Siegel, Breazeal, & Norton, 2009), and subject's personality (Walters et al., 2005).

Later, Kidd and Breazeal, (2005) have highlighted three important factors that vastly contribute on maintaining and creating positive relationships between robot and users. These three concepts are; trust, engagement, and motivation. In order to foster helpful and good relationship between robots and the users, the robot must be capable to engage the user as a jumpstart to interact with the robot. Then, the robot will motivate users to carry out a particular action once they have engaged. Moreover, the robot must be trustworthy enough in helping users to perform a particular task (Kidd & Breazeal, 2005).

Based on the previously mentioned explanations, it can be derived that companion robots are designed to interact with people in a human-centric term and to operate within their living environment. Furthermore, these robots interact with people in an interpersonal manner, interacting and coordinating their behaviour with human through verbal and non-verbal modalities. Due to this interaction, people tend to anthropomorphize digital artefacts and to reason about their behaviour in terms of having their own mental states (e.g., thoughts, intents, beliefs, and desires). These essences are important concepts to be integrated in this study.

2.6.2 Embodiment of Robots

Embodiment plays an essential role in cognitive science and artificial intelligence as algorithm alone is insufficient to regulate subtle interaction between humans and robots (Ziemke, 2001). Embodiment can be classified into five different types, namely; (1) structural coupling between agent and environment, (2) physical embodiment, (3) organismic embodiment of *autopoietic* (living system), (4) *organismoid* embodiment (humanoid robot), and (5) historical embodiment as the result of a history of structural coupling (Ziemke, 2001). Also, researchers in embodiment of an artificial artefact domain have been widely studied an embodiment concept in order to design the most effective artefact on its users (Hone, Akhtar, & Saffu, 2003; Vossen, Ham, & Midden, 2009; Wrobel et al., 2013). In the area of robotics, embodiment plays an important role in developing physical companion robots to increase engagement with its users compared to personal digital assistants (PDAs) (Mataric, 2005). Comparative studies have made to investigate the effects of a physical embodiment pertinent on how people interact differently with physically over virtually developed agents (computer simulated) (Wainer, Feil-Seifer, Shell, & Mataric, 2007; Wrobel et al., 2013; Kawaguchi, Kodama, Kuzuoka, Otsuki, & Suzuki, 2016; Batula, Kim, & Ayaz, 2017; van Maris, Lehmann, Natale, & Grzyb, 2017). In literature, several attempts have incorporated the concept of embodiment in the robotic design (Breazeal, Dautenhahn, & Kanda, 2016). This implementation led to recognize three types of embodiments. These types are; (1) human-like embodiment, (2) creature-like embodiment, and (3) neither humanoid nor animal-like (however, it is still having social attributes). Table 2.4 summarizes selected robots with aforementioned physical embodiment concepts. In addition, the key challenge in designing human-like robots is to avoid the *Uncanny Valley Dilemma* where the appearances and the movement of the robot more of an animate body than a living system. Robots design that falls within Uncanny Valley always associated with negative reaction from human (Mori, 1970). In addition, it may be worth mentioning that that a more human-like design does not necessarily correlate with a "better" design. One needs to balance the robot design with the task, user, and context (Breazeal, Dautenhahn, & Kanda, 2016).

Table 2.4

Selected Physical Embodied Robots

No.	Robot	Feature	Domain	Reference
1	*ROMAN*	Human head-like appearances (i.e., skin and eyes)	Human-Robot Interaction	(Berns & Hirth, 2006)
2	*ANDROID*	Human-like appearances (i.e., it has skin, eyes teeth, and hair)	Human-Robot Interaction	(Breazeal, Dautenhahn, & Kanda, 2016)
3	*KASPAR*	child-like appearances	Autism	(Dautenhahn et al., 2009)
4	*AIBO*	Complete Dog-like appearances	Entertainment	(Fujita, 2004)
5	KISMET	Neither human-like nor animal-like appearances, but it has social attributes (eyes, lips, and ears)	Social interaction	(Breazeal, 2004)
6	*KEEPON*	Toy-like appearances (i.e., rubber skin, eyes, and noise) using *squash and stretch* for showing its expressions	Domestic and autism	(Michalowski, Sabanovic, & Kozima, 2007)
7	*ZENBO*	Toy-like appearances with whole-body motion and touchscreen displaying a face with emotions	Domestic	(Bogue, 2017)

Previous research works have pointed that designing physical embodiment of robot is recommended due to the effects of social presence, trust and empathy (Zlotowski et al., 2016). For example, Kidd and Breazeal (2004) have investigated the effects of embodiment of social robot and animated character on the users' perception in terms of trusting, reliable, helpful, and engaging with robots. The results have confirmed the physical embodied agent scored better results in terms of credibility, informative, enjoyment compared to the fictional character. Also, Bainbridge, Hart, Kim, and Scassellati (2008) explored the effect of physical embodiment of social partner robot on users' perception by comparing physical and video-displayed robot during the book-moving task. The experimental results have proved that subjects cooperated with both platforms of robots but more likely to fulfil unusual instructions given by a physical robot rather than the video-displayed ones. This confirmed the preference in physical robot as it is more trustworthy in regulating human-artefact cooperation.

Moreover, in healthcare domain, Fasola and Mataric (2011) have examined the role of physical socially assistive robot over virtual robot in providing physical exercise for elderly people and subjects' preferences in both types of robots as well. The results indicated respondents are strongly preferred physical embodiment of a physical robot over the virtual robot. The findings had also shed light on the positive characteristics of physical embodiment such as usefulness, enjoyment, helpfulness, social attraction, and social presence.

Another reason that makes physical embodiment of robot preferred is due to its ability to empathize its users. For example, Berland and Wilensky (2015) have studied how embodiment of robot has impact on empathizing people while interacting with physical or simulated robots. The experimental results demonstrated respondents who have interacted with a physical robot felt the sense of empathy than those interacted with a virtual robot. The aforementioned studies have shown identical positive effects related to the embodiment of robot that provide a key idea of this study.

2.6.3 Applications of Companion Robots

Companion robots are becoming an important part in our future daily lives due to its sociable ability. These robots can perform particular tasks but do so in a socially acceptable manner. They have been used and studied in various domains such as education, therapy, entertainment, and human assistance (Eguchi & Okada, 2017). For example, the famous companion robots in market, named Nao and Peeper, developed by SoftBank Robotics (formerly Aldebaran Robotics) have been used widely in various educational settings and in therapies (i.e., autistic children) (Tapus et al., 2012; de Jong et al., 2018; Eguchi & Okada, 2018; Lytridis, Vrochidou, Chatzistamatis, & Kaburlasos, 2018; Schicchi & Pilato, 2018). Other well-known companion robots are Jibo and Zenbo. These robots are considered as the state of the arts in the development of companion robots due to these features; 1) being sociable (having sophisticated interaction capabilities, often both verbal and non-verbal), 2) permit domestic applications (designed specifically for use in the home), and 3) available for a relatively affordable price (ranging from USD 400 to 700) (Zlotowski et al., 2016).

Within research labs, several companion robots were developed to demonstrate basic and complex social assistantships. Examples of these robots are; (1) Autom for a weight loss management programme (Kidd & Breazeal, 2008), (2) AIDA as a driving navigator (Williams, Flores, & Peters, 2014), (3) Casper as a kitchen assistant for elderly populations (Bovbel & Nejat, 2014), (4) Paro as a therapeutic tool (Inoue, Wada, & Uehara, 2012), and (5) iCat in studying different aspects in human-robot interaction (van Breemen, Yan, & Meerbeek, 2005). Figure 2.5 shows these examples of companion robots.

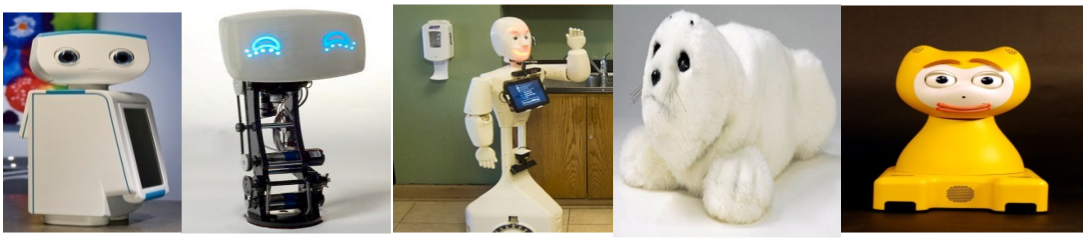

Figure 2.5. Examples of Sociable Robots (left to right: Autom, AIDA, Casper, Paro, iCat)

Table 2.5 shows a summary of other companion robots and its application domain.

Table 2.5

A *Summary of Companion Robots*

No.	Robots	Concepts	Domains	References
1	TinkRBook	For child-parent reading process enhancement	Education	(Chang & Breazeal, 2011)
2	PANDA	In-car entertainment for kids	Entertainment	(Gordon & Breazeal, 2015)
3	MiRo	Animal-like companion robot for studying human-robot interaction	Research /Education	(Prescott, Mitchinson, & Conran, 2017)
4	HealthBot	A home companion for elderly	Healthcare	(Jayawardena, Kuo, Broadbent, & MacDonald, 2016)
5	KASPAR	A therapeutic companion for autistic children	Healthcare	(Robins & Dautenhahn, 2014)
6	BARTHOC	A humanoid-like robotic platform to study human behaviours	Education	(Hackel, Schwope, Fritsch, Wrede, & Sagerer, 2005)

Through the emergence concept of Industrial Revolution 4.0, these companion robots are considered as the state-of-the-art in the field of robotic technology and the development of such kind of robots is becoming inevitable phenomena. Next section deals with the concepts of learning and reading.

2.7 Learning and Reading

Learning and reading are two associated terms that have been used extensively in educational spectrums. Reading is considered as an essential part of learning process and incredibly shifted from "*learning to read*" to "*reading to learn*" (Sullivan & Puntambekar, 2015). From the perspective of *reading to learn*, readers must comprehend the written text in meaningful ways to form an integrated representation of related ideas that enable them to be used it in relevant contexts. However, some learning difficulties such as Dyslexia impedes the learning process through reading (Ellis, 2014) and language comprehension (Klingner, Boelé, Linan-Thompson, & Rodriguez, 2014). These problems are out of the scope for this study.

Nevertheless, one notable problem that hinders a reading process is the formation of cognitive load that influences the learning outcomes (Choi, van Merriënboer, & Paas, 2014). For example, reading to learn for technical subjects (such as mathematics, physics, and chemistry) is one of the most difficult materials and took more efforts if readers have to face more concepts per word, per sentence, and per paragraph than other subjects (Braselton & Decker, 1994). Therefore, learning process through reading will be affected by cognitive overloading issues that results a low reading performance (Sweller, Ayres, & Kalyuga, 2011; Paas & Sweller, 2012; Choi et al., 2014). Next sections deal with the concepts in reading and reading types.

2.7.1 Concepts in Reading

Normally, reading processes aim to increase the knowledge about particular areas and construct characters and maturity, sharpens thinking, and widens awareness in related-chosen issues (Al-Husaini, 2013). Buscher et al. (2012) have defined reading as one of the most frequent activities of knowledge workers. The demands of reading have changed where reading is no longer reflected either for entertainment or intellectual exercises, but it also considered as an essential component in daily activities. Also, being competent at different types of reading gives insurance of survival in a modern society (Rupley & Gwinn, 2010).

Alexander and Laboratory (2012) have illustrated the concept of reading as a multidimensional, developmental, and goal-directed in nature. The multidimensional idea of reading is due to the orchestration of cognitive, neurophysiological, sociocultural, motivational, and cognitive factors that are required while reading. The developmental perspective related to the reading is not innate, but it is a complex capability acquired over time and changes across lifespans as consequences of human experiences, knowledge, and beliefs during reading (Fox & Alexander, 2011; Alexander & Laboratory, 2012). Reading in a sense of a goal directed and intentional brought together the interrelation between readers and the intention of the written text by the authors.

On the other hand, reading comprehension is defined as the process to simultaneously extract and construct meaning through the interaction and involvement through written language. There are three imperative factors to facilitate this type of reading, namely; the reader, the text, and the type of reading activity (Snow, 2002). First, the reader's characteristics that involve *cognitive abilities* (i.e., attention, critical analytic ability, inferencing, memory, and visualization), *motivation* (i.e., self-efficacy as a reader, the purpose for reading interest in the content), *knowledge* (vocabulary and topic knowledge, discourse knowledge and linguistic, knowledge of comprehension strategies), and *experiences*. Second, the text effects on reading by the way the text is presented to the reader as electronic text is showing challenges to reading comprehension (i.e. dealing with non-leaner nature of hypertext) (DeStefano & Leevre, 2007). The activity refers to the intention of reading where the initial purpose of an activity can change throughout the processes.

Moreover, materials (e.g., printed vs. electronic) also play an important role in facilitating reading. For example, some studies showed readers do not limit themselves only to either print or electronic media, but often use both (Shelburne, 2009; Foasberg, 2011, 2014). Additionally, the effect of media during reading has been examined as well. For example, Mangen, Walgermo, and Brønnick (2013) have found that participants who read a printed-text format scored significantly higher than those who read only an electronic format for reading comprehension test (Mangen, Walgermo, and Brønnick, 2013). From technical perspective, Wästlund, Reinikka, Norlander, and Archer (2005) have reported readers experienced a higher level of stress when using computers compared to the printed materials. In the same vein, reading a digital materials may increase the risk of cognitive overload as well (Wästlund, 2007).

Furthermore, there are several studies were conducted to investigate issues of reading such as reader-text interaction (Eason, Goldberg, Young, Geist, & Cutting, 2012), strategies in reading (Alsheikh & Mokhtari, 2011; Bjorklund, 2013; Ford, 2014), reading skills (Herbers et al., 2012; Burgoyne, Baxter, & Buckley, 2013; Yang, 2014), reading habits (Marschark et al., 2012; Dilshad, Adnan, & Akram, 2013; Applegate et al., 2014), reading behaviour (Grzeschik, Kruppa, Marti, & Donner, 2011; Schiefele, Schaffner, Möller, & Wigfield, 2012; Wang, Bao, Ou, Thorn, & Lu, 2013), difficulties in reading (Griffin, Burns, & Snow, 1998; Torgesen, 2002; Suárez-Coalla & Cuetos, 2015), and intervention programs to give an aid while reading (Elbaum, Vaughn, Hughes, &Moody, 2000; Chang, Nelson, Pant, & Mostow, 2013).

In term of reading difficulty, there are three levels of reading based on the complexity of written text. These levels are; (1) an independent level where those materials were designed with good comprehension and recall, (2) an instructional level where readers do satisfactory reading based on some instructions to read, and (3) a frustration level where reading skills become poor, faulty comprehension, ,obvious signs of tension, and negative emotion becomes obvious (Hunt, 1970; Treptow, Burns, & McComas, 2007; Stange, 2013).

Pertinent to the reading problems, they are highly dependent to the type of reading. For example, reading to learn or acquire knowledge is associated with a high level of cognitive load (Hümeyra & Gülözer, 2013). Moreover, experienced cognitive load for specific tasks (e.g., reading to learn new information) is always associated to a number of negative symptoms such as stress (Conway, Dick, Li, Wang, & Chen, 2013), anxiety (Chen & Chang, 2009), fatigue (Mizuno et al., 2011). Those precursors may lead to the experiences of overloading and disengagement, that later reduce the intended reading task performance (Leppink, 2014). Also, other physical symptoms such as eyestrain, tired eyes, and irritation may reduce reader's ability to comprehend reading materials (Blehm, Vishnu, Khattak, Mitra, & Yee, 2005).

2.7.2 Types of Reading

Reading has been defined as a highly complex skill that is prerequisite to success in many modern societies where a great deal of information is communicated in written forms (Rayner, Pollatsek, Ashby, & Clifton, 2012). Also, readers apply different strategies during reading process (e.g., repeated reading, notes taking) and always read for different purposes (e.g., reading for pleasure, reading for the gist, reading to write and learn) (Stoller, 2015). Weir and Khalifa (2008) have detailed-up the process in reading based on its difficulty levels. These levels are (1) scanning or searching for local information, (2) careful local reading, (3) skimming for gist, (4) careful global reading for comprehending main idea, (4) search reading for global information, (5) and careful global reading to comprehend a text. Based on the previous discussions, the current study majorly focuses on reading that leads to learning or to answer some questions. Hence, the reader needs to put some efforts to learn the new information.

2.8 Cognitive Load and Reading Performance

Total amount of mental resources that is imposed on a person while trying to solve a particular problem or to achieve a certain task is called cognitive load (Sweller, van Merrienboer, & Paas, 1998). This concept is based on the limitation of a working memory to function properly due to the limited capacity of a person to process novel information (Chandler & Sweller, 1991; Paas, Tuovinen, Tabbers & van Gerven, 2003). One of the major evidences is the 7 ± 2 principles where the executive control peripheral (working memory) is limited to process incoming (perceived) information. The bounded function of working memory is the particular reason in determining human's memory capacity (Miller, 1956; Kolfschoten, 2011). As a consequence, it will result an individual to experience cognitive overloading (Chen et al., 2012; Chen

& Epps, 2013). In addition, cognitive load is defined as the executive control of working memory forced by tasks and the reflection of pressure individuals feel upon completing the task (Paas et al., 2003). The cognitive load perspective can be viewed in two dimensions; task-based dimension (i.e., mental load imposed on the person by the task itself) and/ or an individual-based dimension (i.e., mental effort / load to accomplish the task) (Sweller et al., 1998). In regard to these dimensions, the mental load dimension is the portion of cognitive load forced by the task and the environment, while the mental effort dimension relates the amount of cognitive capacity within any individuals (van Gerven, van Merriënboer, Paas, and Schmidt, 2000).

Cognitive load concept can be distinguished into six types. These types are; (1) attentional demands (attention shifting while performing a task), (2) response demands (passive/ active response to the stimuli), (3) familiarity (familiar or non-familiar information decrease or increase cognitive load), (4) memory demands (trials to remember particular information), (5) processing demands (multi-tasking and tasks switching), and (6) processing difficulty (challenges while performing a task) (Block, Hancock, & Zakay , 2010).

In addition, in the field of human-computer interaction, cognitive load has been defined as the available mental resources of human to solve problems or complete tasks in a given time and it depends on the amount of information or elements to be handled concurrently (Oviatt, 2006). For example, cognitive load generally depends upon individual differences (e.g., prior knowledge, motivation), the task itself (task difficulty), and environmental factors (e.g., stress, attention, distraction) (Oviatt, 2006).

Moreover, cognitive load can be viewed as complex, data intense, and time critical situations due to the complex interaction designs or as the difficulty of the task (Khawaja, Chen, Owen, & Hickey, 2009). For instance, it can be caused by multimodal interfaces and unnecessary contents (Mayer, 2002). Moody (2004) reported that the reduction of cognitive load is correlated to the increasing level of reading comprehension. Albeit the negative effects of cognitive load, some studies have shown that with an appropriate level of cognitive load, it optimizes individual's task-performing level. Therefore, it is imperative to maintain the optimal range of a cognitive load level for productivity maximization (Hussain et al., 2011).

Cognitive load also exists in other part of human activities, such as driving. For example, the driver experiences attention interference due to expected and unexpected disruptions such as people or animals crossing in front of the car or even to the abrupt change of lanes (Lee, Lee, & Boyle, 2007; Cobanoglu, Kindiroglu, & Balcisoy, 2009). There is also increasing of cognitive load while switching the attention between virtual/information places and physical places (i.e., using a global positioning system (GPS) application while driving) or alternating between two different interfaces like laptops and smart phones (Ho & Spence, 2005). Therefore, the experienced cognitive load can influence affective status of an individual through frustration or boredom (Kalyuga, 2011c) and other psychological problems such as stress (Niculescu, Cao, & Nijholt, 2010), fatigue (Roy, Bonnet, Charbonnier, & Campagne, 2013), and anxiety (Chen & Chang, 2009).

Similar conditions also can be observed in train traffic management due to its complex operation and process (Neerincx, Harbers, Lim, & van der Tas 2014). Thus, high mental resources must be applied to decrease potential negative consequences (i.e., accidents and overlapping trails). Table 2.6 summarizes the drawbacks of cognitive overload in various domains.

Table 2.6

Summarization of Cognitive Load in Various Domains

No.	Domains	Examples	Consequences of High Load	References
1	Reading and learning	Reading technical subjects such as mathematics, physics, and chemistry	Less comprehension, disengagement during reading, frustration, tiredness, lack of focus, etc.	(Choi et al., 2014; Behroozi, Lui, Moore, Ford, & Parnin, 2018)
2	Aviation	Fighter pilots and naval operators during decision-making tasks	Less attention while performing a task and thereby the safety will be directly affected as well as bad decision making will be made	(Behroozi et al., 2018)
3	Driving	Drivers while witching the attention between virtual/information places and physical places	Serious accidents that might be lead to death	(Endres, 2012; Williams & Breazeal, 2013)
4	Train/ traffic management	controllers while managing too much	Accidents and overlapping trails that affect the safety	(Neerincx, Harbers, Lim, & van der Tas 2014)

When it comes to learning process, cognitive load is one of the serious issues that impose negative consequences on readers' performance. For instance, new learner/ reader will experience cognitive overload effect due to the limited capacity of working memory through time (De Jong, 2010). It is also related to task difficulty and learner characteristics (Choi et al., 2014). As a solution, instructional designs have been introduced to curtail the effects of cognitive load in learning (van Merriënboer & Sweller, 2005; Scheiter, Gerjets, Vollmann, & Catrambone, 2009; Sweller et al., 2011; Kalyuga, 2012).

Instructional designs are the principles in designing a task in such a way to lessen the interactivity within learning elements that later minimize loads on a working memory. However, the implementation of instructional designs will only reduce a fraction of load (i.e, extraneous load), while preserving another load (Sweller et al., 2011). A number of studies have shown instructional designs have been used to control or manage the level of cognitive load through minimizing the interactivity between task's learning elements (Sun, Anand, & Snell, 2017; Refat & Kassim, 2018; McMullan, 2018). Hence, designing less complex contents or interfaces will reduce potential risks in cognitive overloading formation (e.g., e-learning). However, as different circumstances might need different designs, the basic design will not be suitable to serve different range of materials and contents due to its complexities. Moreover, it limits the dynamics implementation for any digital applications, as a new user interface design must be acquired if the contents were changed.

2.8.1 Cognitive Load Theory

Cognitive Load Theory (CLT) is one of the most prominent theories in instructional domains based on the understanding of human cognitive architecture (Sweller et al., 2011). Introduced in late 80's, CLT aims to explain how people process information (Sweller, 1988). The CLT building blocks are highly associated to these two components, namely; working memory (WM) and long-term memory (LTM) (Sweller, 1988; van Gerven et al., 2000; Sweller et al., 2011). The long-term memory refers to the unlimited human's knowledge base capacity and duration to hold information (Kalyuga, 2011c). Within the long-term memory, the information is stored as organized schemas, which governs the behaviour of an individual. With certain practice, these schemas can be automated and used fluidly by humans (Sweller et al., 2011). Contrary, the working memory refers to the mechanism that limits the scope of instantaneous change in the knowledge base (with limited information due to its limited capacity and duration) (Sawicka, 2008).

From CLT perspectives, there are three different types of load (Intrinsic, Extraneous, and Germane) that can impair cognitive capabilities (Sweller et al., 2011). First, the intrinsic load represents experienced load that imposed by the complexity of the acquired knowledge (Sweller et al., 2011), or the complexity of the task itself (Choi et al., 2014). Second, the extraneous load represents the load that has been imposed on a person due to the way and how information is presented (Kolfschoten, 2011) and environmental factors (e.g., noise, or extreme temperature) (Choi et al., 2014). Lastly, the germane load is related to the resources within working memory that handle both intrinsic and extraneous loads as a positive outcome from the acquired new information (Kalyuga, 2011c). The interaction of these loads is visualized in Figure 2.6. Moreover, all loads must be within the limits of mental resources and the amount of cognitive load on working-memory.

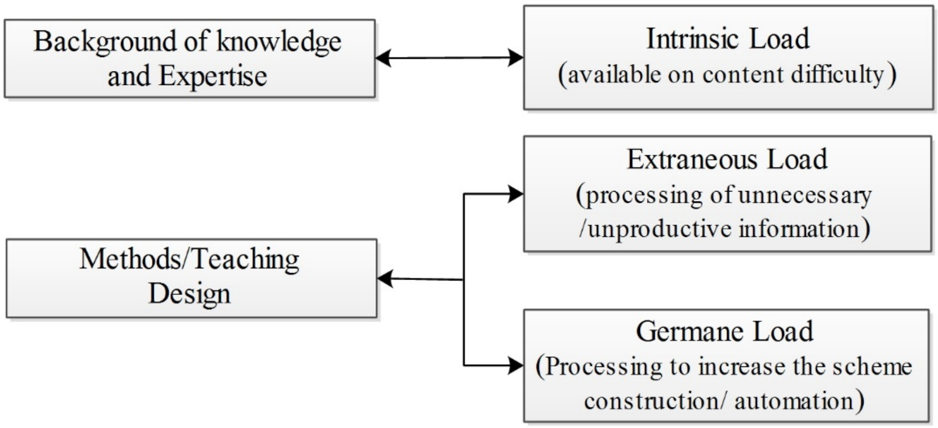

Figure 2.6. Components in Cognitive Load (Jalani & Sern, 2015)

CLT has been widely used in various domains such as in; education constructs for medical students (Young & Sewell, 2015), hypermedia system (Schultheis & Jameson, 2004), aging and learning (van Gerven et al., 2000), affective computing (Kalyuga, 2011c) and programming tutorials (Young, van Merrienboer, Durning, & Cate, 2014).

2.8.2 Paas and van Merriënboer Model of Cognitive Load

Researchers in educational psychology domains have defined cognitive load as one of the critical factors in affecting learning processes and problem-solving tasks (Sweller et al., 2011) and has been used to explain learners' difficulty during problem solving processes. As this concept gives critical implications of cognitive load on learners and to understand the factors that generate cognitive overload, a conceptual framework that elucidates the main factors causes cognitive load while performing selected tasks was introduced by Paas and van Merriënboer (1994) (as shown in Figure 2.7).

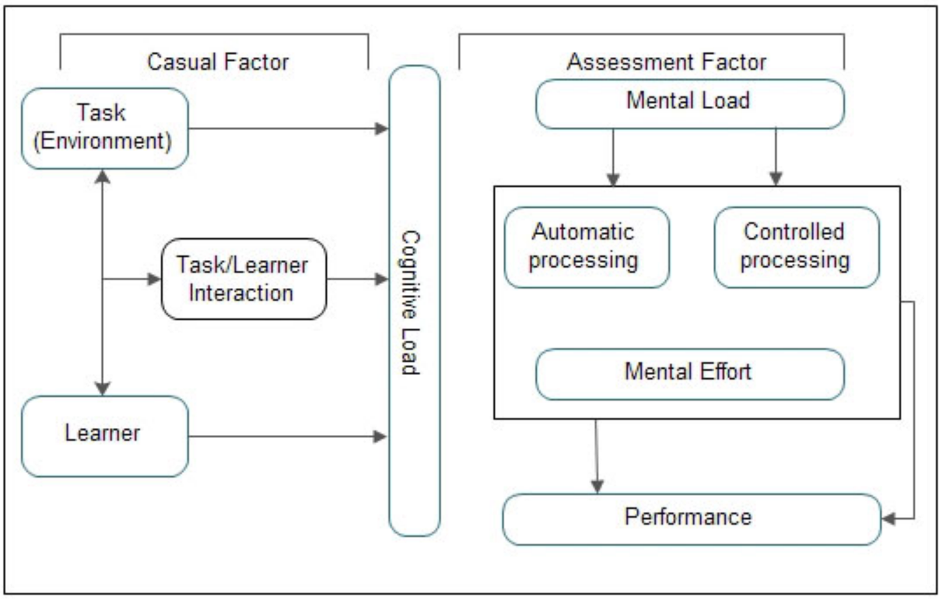

Figure 2.7. Conceptual Framework of Cognitive Load (adopted from Paas and van Merriënboer (1994))

This model is divided into two parts, namely; causal and assessment factors. The combination between task characteristics (environment, time pressure) and learner characteristics (cognitive abilities, expertise, motivation) together with its interaction are presented as causal factors related to the state of cognitive load. Some studies captured the interaction between learners' and learning-task characteristics in various perspectives such as expertise-reversal effect (Kalyuga, Ayres, Chandler, & Sweller, 2003; Kalyuga & Renkl, 2010), and learning age and learning–task characteristics (Paas, Camp, & Rikers, 2001; van Gerven, Paas, van Merriënboer, & Schmidt, 2006). Hence, selected task should be based on the characteristics of leaners (e.g., the non-expert learners should not be assigned to solve complex tasks).

From Figure 2.7, it shows the interplays between task-centred, and subject independent dimension that represents close-dependence on the characteristics of the task itself and complexity of the task to impose cognitive load. The mental effort assessment is considered as a human-centred dimension, which means it is the amount of capacity or available resources the learners have to accommodate in solving complex tasks. Moreover, it shows that mental effort reflects the interaction between learners and the characteristics of the task with the amount of controlled processing during learning engagement. Besides that, this model also described the formation of CL as a result from the interaction between task performance, mental effort, and potential errors. Results from experiments conducted by Paas et al. (2003) in several domains have indicated similar phenomena.

However, this model is unable to elucidate the details of the causal factors as it considered cognitive load as a result from the interaction between task and learner characteristics. Also, this model neglected the effects of physical environment (Choi et al., 2014). Therefore, a new revised model was designed to include the side effects from physical environment on learners such as light intensity, overwhelm sound, temperature, and design principles for learning materials (Choi et al., 2014). Figure 2.8 summarizes the revised model by incorporating concepts in cognitive load, physical environment, and learning performance.

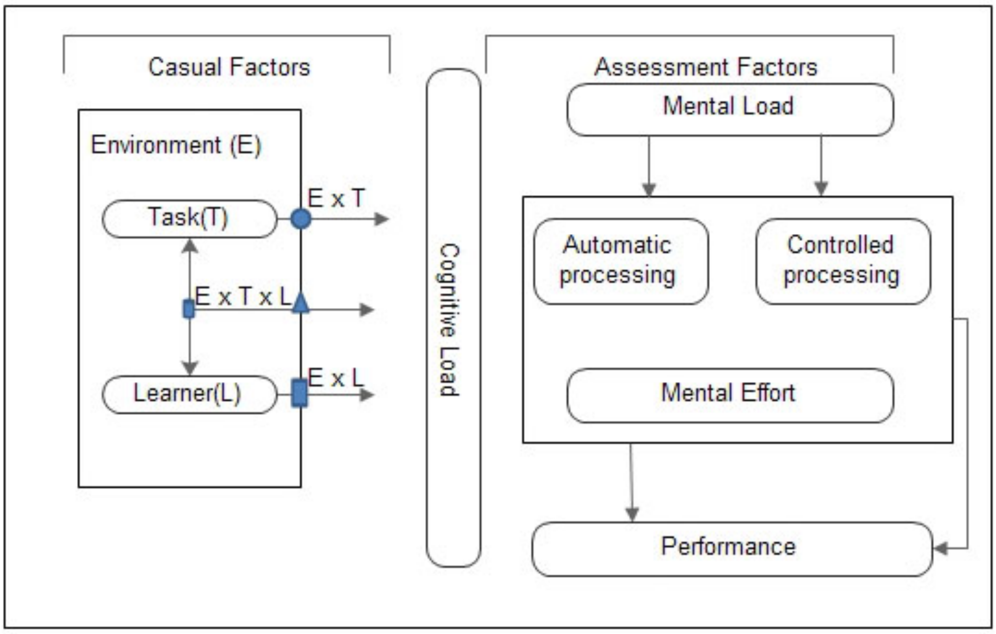

Figure 2.8. The Revised Model of Cognitive Load (Choi et al., 2014)

However, the revised model is not robust enough to explain the interchange between each component such as interaction in attention (Cierniak, Scheiter, & Gerjets, 2009), expertise (Chin, 2007), motivation (Paas et al., 2005), and cognitive impairment.

2.8.3 Dynamics Model of Cognitive Load

CLT has been playing a dominant role in a number of domains since it was introduced decades ago. As the concepts in psychology and cognitive sciences are expanding due to the introduction of new methods, measurement devices and experiments, a number of new models have been developed. For example, Sawicka, (2008) developed a model to represent the effect of CLT corresponded to the learners' abilities in acquiring new information. This model is dynamic (changes over time) and used to explain CLT from the human cognitive architecture views. This model has paved ways to develop a formal model to understand the dynamical interplays between related concepts (e.g. unstructured relationships within the existing concepts in previous theories).

This model incorporates all existing elements within cognitive load theory such as Intrinsic (ICL), Extraneous (ECL), and Germane (GCL) elements of human cognitive architecture (Working Memory (WM), schema (Long-term Memory (LTM)) as well as the complexity of the learning materials when processing new materials. These interplays are depicted in Figure 2.9. From this model, a Complexity of Revealed Material (CRM) refers to the difficulty of the task presented to the leaner while Relevant Schema (RS) refers to the existing knowledge of the leaners. CRM-RS gap always occurs when learning materials are difficult to be learnt and readers have not enough knowledge to absorb the task difficulty. The gap between prior knowledge and task difficulty leads to the development of an intrinsic load (ICL) that occupies some parts in working memory (WM). In this case, an extraneous cognitive load (ECL) will be triggered and also consumes the existing parts in working memory. Thus, the remaining cognitive space within working memory to learn the task will be dedicated to Germane Cognitive Load (GCL). GCL is important to construct new schemas in long-term memory (LTM). These new schemas provide an efficient way to organize interrelated concepts in a meaningful way.

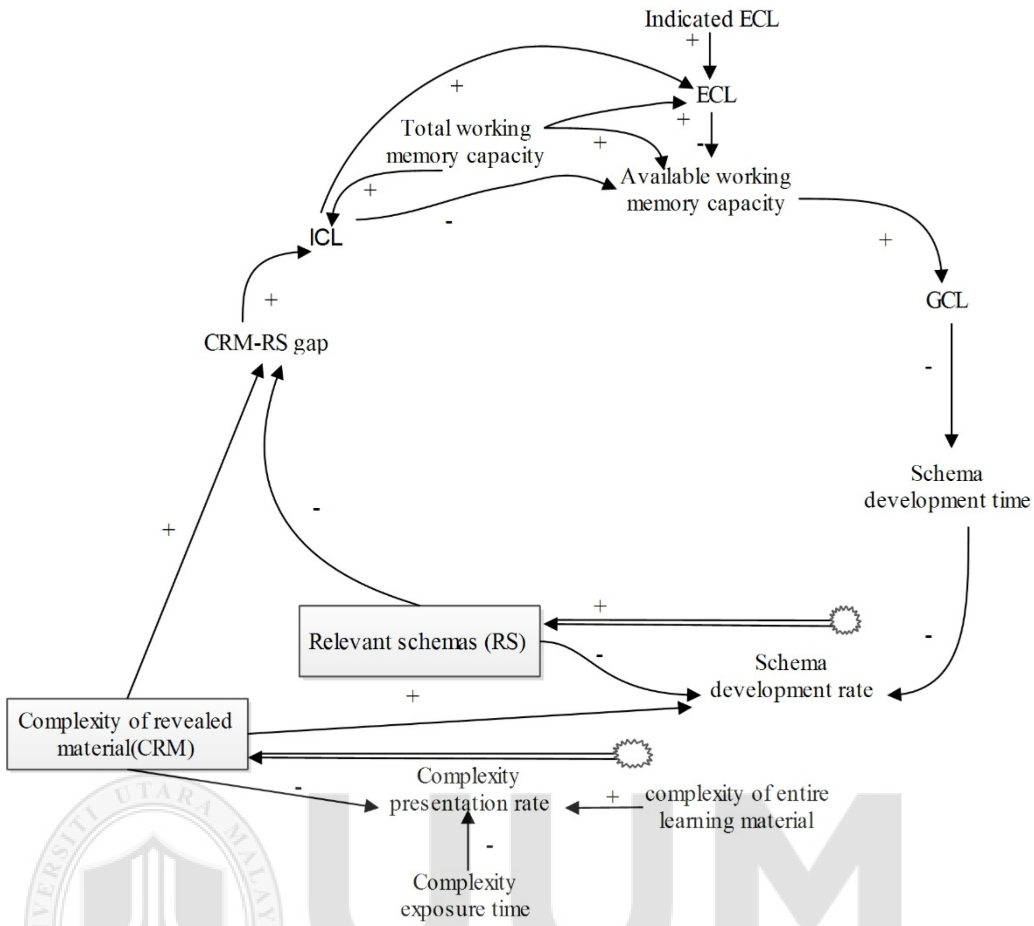

Figure 2.9. The System Dynamic Model of a Cognitive Load Theory

Nevertheless, the developed model explained the effects of difficult materials by illustrating the interplays between all CLT factors, the design of learning materials, and the fundamental elements of a human cognitive architecture. However, it neglects some important factors on different types of cognitive load and its great influence on the performance of leaning (e.g., environment (Choi et al., 2014) and motivation (Paas et al., 2005), experience (Chin, 2007), attention (Cierniak et al., 2009)). Therefore, a deeper understanding of how these factors are interrelated to cognitive load is needed. Moreover, this model could not able to be incorporated in any digital artefact due to incomplete criteria to measure the aforementioned concepts. Furthermore, it has to be verified and validated as well.

2.8.4 Cognitive Theory of Multimedia Learning

The underlying principles of effective learning through multimedia in terms of cognitive load have been explained in Cognitive Theory of Multimedia (CTM) (Mayer, 1997, 2005). This theory provides a grounding aspect to observe the effectiveness in conveying meaning by combining both words and pictures. The theoretical foundation of this theory was drawn from several cognitive theories such as Dual Coding Theory (Clark & Paivio, 1991), Cognitive Load Theory (Chandler & Sweller, 1991), Generative Theory (Wittrock, 1989), SOI model of Meaningful Learning (Mayer, 1996), and Baddeley's Model of Working Memory (Baddeley, 1992).

Three different assumptions were used to explain how processing information on multimedia environment affects learner's cognitive load level (Mayer, 2005). First, the dual channel assigns different channel to process information from both visual and verbal sources. Second, a limited capacity explains the effect when only limited resources are available for each channel to process both verbal and virtual materials. Third, an active processing approach to explain that learning requires an extensive cognitive processing for both verbal and visual channels (Mayer & Moreno, 2003).

Figure 2.10 depicts the cognitive theory of multimedia learning and how learners process the information during new learning tasks.

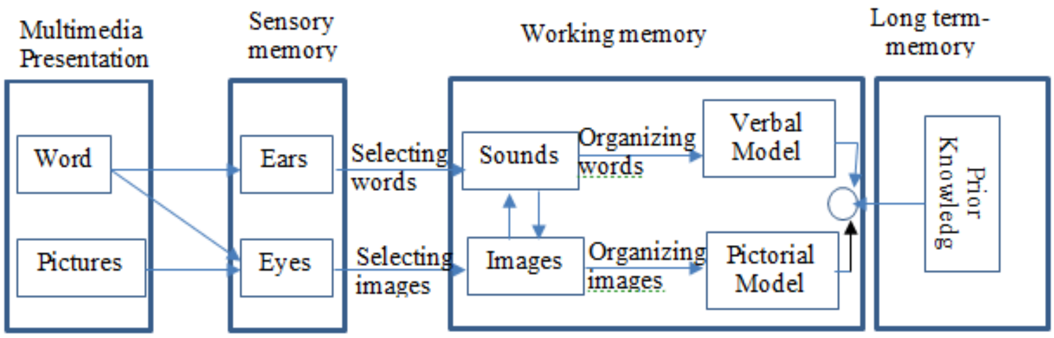

Figure 2.10. Cognitive Theory of Multimedia Learning

From Figure 2.10 the diagram provides a visual understanding on how learners may encounter cognitive overload within their cognitive processing when dealing with multimedia learning materials. Additionally, it shows the effect of working memory limitation and low prior knowledge towards the formations of cognitive load. This theory has been applied as a basic building block in reducing the negative effects from high cognitive load for multimedia-based learning materials (Lopez & Andres, 2014; Moradmand, Datta, & Oakley, 2014).

2.8.5 Cognitive Task Load Model

Cognitive load has also linked to the demanding task and operator performances while handling difficult and time specific tasks (Neerincx, Veltman, Grootjen, & Veenendaal, 2003). The main philosophy of this model is to develop a smart system in assisting operators when performing the unfamiliar task that might impair their capacity and lead to the decision-making errors. This model has differentiated three types of load that affect operator performance and mental efforts. These are; (1) percentage of time occupied while performing the task, (2) the level of information processing, and (3) task-set switches. Time occupied refers to the maximum total amount of time needed to accomplish specific tasks. For example, an operator should spend not up than 80 percent of the total time available. Due to the complex task situation, especially with many sub-tasks, switching between tasks behaviour is an indicator towards the formation of cognitive load as well. Also, this model concentrates in combining all load elements to determine the cognitive load as imposed by task demand (as depicted in Figure 2.11).

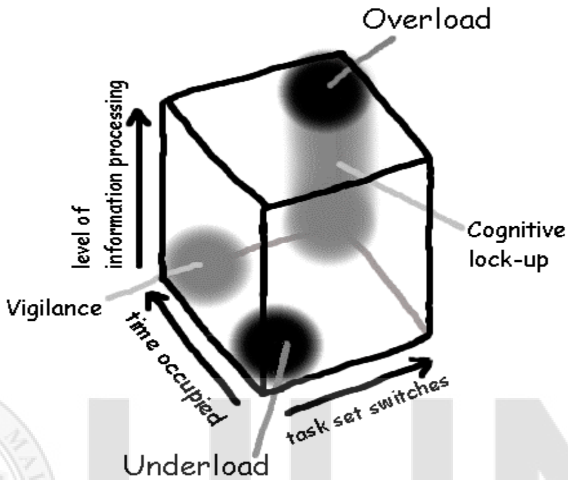

Figure 2.11. Three -Dimension Model of Cognitive Task Load (Neerincx, 2003)

Another well-known problematic task for an operator that increases over time is vigilance. Prolonged vigilance can result in stress due to the specific task demands (i.e. the requirement to continuously pay attention on the task) and boredom that appears with highly repetitive and homogeneous stimuli. In the same case, the cognitive-lock up is one of the fundamental problems of the operators have to face as they need to manage their own tasks adequately. Overall, the model has shown task allocation (task-switches) is a solution to overcome operators' cognitive load problems.

2.9 Cognitive Load Measurement

The measurement techniques for cognitive load is becoming important as it shows the amount of mental efforts imposed on a person to complete a particular task and by determining the level of CL, it provides insights to ensure better performances

(Hussain *et al*., 2011; Chen & Epps, 2013; Hussain, Calvo, & Chen, 2013). There are three widely accepted techniques for measuring cognitive load, namely; (1) subjective-measurement (self-rating), (2) task-performance measurement, and (3) behavioural and physiological measurement. The details of these three measurement can be found in Paas, van Merriënboer, and Adam, (1994), Brunken et al. (2003), Khawaja et al. (2009), Nourbakhsh, Wang, and Chen, (2013), and Hussain, Calvo, and Chen, (2014) works. First, the subjective-measurement or self-rating measurement has been implemented to measure the mental effort experiences by participants after completing the task (Martin, 2014). For example, NASA-Task Load Index (NASA_TLX) is one of the cognitive load measurements developed by Hart & Staveland, (1988). NASA_TLX is a multidimensional subjective measure that integrates measurements of perceived frustration, effort, and physical, mental and temporal task demands (Gog, Kirschner, Kester, & Paas, 2012). This technique has been used in measuring the work load among nurses (Hoonakker et al., 2011). Second technique is a uni-dimensional measurement developed by Paas, (1992) which consists of a nine-point scale construct ranges from (1) as *very low* to (9) as *very high* (Gog et al., 2012). This measurement has been used in many psychological studies to capture the level of load imposed by a learning task (Sweller et al., 2011; van Gog & Paas, 2008). As an alternative to this, the seven-points scale was developed to evaluate cognitive load by preserving the original formal scaling method (Kalyuga, Chandler, & Sweller, 1999).

On the other hand, the dual-task or performance measurement was also used as an objective technique focuses on either performance on the task itself or performance on the dual task (secondary task) in assessing the level of cognitive load (Brünken, Steinbacher, Plass, & Leutner, 2002). This method has been applied in various studies to measure either human performance will be increased with lesser load or vice versa

(Endres, 2012; Harbluk, Noy, Trbovich, & Eizenman, 2007). This approach can be considered as more objective than self-rating due to its less disruptive in nature. The third technique is physiological and behaviour measurements. This method is intrusive due to the implementation of some bio-sensor devices such as electrocardiography instruments to measure the electrical activity of the heart of a period time (Durantin, Gagnon, Tremblay, & Dehais, 2014; Al-Hazzouri, Haan, Deng, Neuhaus, & Yaffe, 2014) and an eye tracker device to measure the point of gaze or motion of an eye relative to the head (Palinko, Kun, Shyrokov, & Heeman, 2010; Chen, Epps, Ruiz, & Chen, 2011). The usage of these devices may cause discomfort for some participants due to its intrusiveness (Schultheis & Jameson, 2004). Another devices can be used to capture cognitive load are speech recognizer (Huttunen, Keränen, Väyrynen, Pääkkönen, & Leino, 2011), pen input (Ruiz, Taib, Shi, Choi, & Chen, 2007), electroencephalography (EEG signals) to capture electrical activity of the brain (Knoll et al., 2011)), and galvanic skin response (GSR) for electrodermal responses (Nourbakhsh, Wang, Chen, & Calvo, 2012).

2.10 Factors and Its Relationships to Cognitive Load

In demanding tasks, cognitive loads are influenced by a set of dynamic factors. This section provides the most prominent factors responsible to cause cognitive load during the demanding tasks (specifically for reading to learn) and its negative consequences. These factors were derived from a number of selected theories, models, and empirical studies related to the cognitive load.

For example, in CLT (Sweller et al., 2011), there are three different factors for cognitive load were identified, primarily to explain intrinsic, extraneous, and germane load. These three factors are examined thoroughly in the literatures to show how a person encounters different types of loads (van Merriënboer & Sweller, 2005; Kalyuga, 2011a). In relation to the human cognitive architecture, both intrinsic and extraneous loads are associated with short-term memory (active memory to process limited information in limited time), while germane load is linked to long-term memory (human knowledge base) (Baddeley, 1992; Kalyuga, 2011a; Orzechowski, 2010; van Snellenberg et al., 2014; Hulme & Mackenzie, 2014).

Based on the Choi's model (2014), (as shown in Figure 2.8), the intrinsic load always occurs due to the task complexity, while an extraneous load relates to the external condition imposed through the effects of physical environments such as noise and temperature. The model shows the usage of knowledge (stored in long-term memory) to tackle task difficulty can be considered as a germane load. Furthermore, this model includes time pressure as an environmental factor contributes to the cognitive load (Galy, 2012). The experimental results in Galy (2012) have asserted the interplays between different factors such as loads (intrinsic, extraneous, and germane), task difficulty, and time pressure.

From another perspective, the condition of physical environments has great impact on the level of motivation. In reading and learning, motivation plays a major role to increase the level of mental exertion (Choi, 2014). Therefore, it is equally important to consider motivation as a complement precursor factor to reduce cognitive overloading. Moreover, motivation provides high willingness to perform a difficult task that later increases in the capacity of working memory to regulate persistence (Schnotz, Fries, and Horz, 2009). Thus, individuals with a high motivational level will allocate more mental efforts for better outcomes than those who are not (Schnotz et al., 2009). In addition, the ability for a highly motivated individual to exert high mental effort is constrained by personality characteristics (e.g., positive personality correlated to high performance in solving difficult tasks) (Rose, Murphy, Byard, & Nikzad, 2002; Parks & Guay, 2009).

Another fact is the level of experience in performing demanding tasks. This concept is essential factor to manage the appropriate level of cognitive load. For example, well-seasoned (highly experienced) individuals will encounter less amount of load compared to the novice individuals (Scheiter, Gerjets, Vollmann, & Catrambone, 2009; Kalyuga, 2012). From this perspective, it is clear to see a positive relationship between the level of experience and long-term memory.

Also, affective state and cognitive load are connected to each other. For example, when a person is experiencing high cognitive load, it will trigger either positive or negative feelings and later influences performance (Kalyuga, 2011c). It means demanding tasks are always accompanied with negative psychological symptoms such as anxiety (Chen & Chang, 2009) and stress (Niculescu et al., 2010) that later hamper the effectiveness in performing the assigned task.

Exhaustion is another condition that is essential to the demanding tasks (either physical or mental exhaustion). Both physical and mental exhaustion give negative consequences such as tiredness that eventually disengage reading processes. In many ways, the experienced exhaustion levels reflect an individual's need for important recovery that arises after sustained expenditure of mental effort to meet the task demands (Sonnentag & Zijlstra, 2006; Esposito, Otto, Zijlstra, & Goebel, 2014). Table 2.7 summarizes important factors related to cognitive load.

Table 2.7

Factors Related to Cognitive Load

No.	Factor	Concept	Reference
1	Intrinsic	Task inflicted load	(Kalyuga, 2011b; Sweller et al., 2011; Paas & Sweller, 2012)
2	Extraneous	The load that associated to the presented task, environment and individual characteristics	(Kalyuga, 2011b; Sweller et al., 2011; Paas & Sweller, 2012)
3	Germane	Generated load as the outcome to process new information	(Kalyuga, 2011b; Sweller et al., 2011; Paas & Sweller, 2012)
4	Motivation	The willingness of an individual to do a certain task	(Schnotz et al., 2009)
5	Persistence	The ability to engage to solve certain tasks	(Schnotz et al., 2009)
6	Personality	Different types of personality have great impacts on the motivation level	(Rose et al., 2002)
7	Short-term memory	An active memory to process current information	(Sawicka, 2008), (Orzechowski, 2010)
8	Long-term memory	Existed or acquired knowledge	(Sawicka, 2008), (Orzechowski, 2010)
9	Task difficulty	The complexity of the assigned learning task	(Galy et al., 2012), (Choi et al., 2014)
10	Time pressure	Limited assigned duration to solve the task	(Galy et al., 2012), (Choi et al., 2014)
11	Physical environment	Environmental conditions such as noise and extreme temperatures	(Choi et al., 2014)
12	Experiences	The acquired of experiences from prior exposures with related tasks	(Scheiter et al., 2009), (Kalyuga, 2011a)
13	Mental exhaustion	It refers to the tiredness of using mental resources (i.e. lack of concentration)	(Esposito et al., 2014)

Table 2.7 continued.

14	Physical exhaustion	Physical related tiredness such as back-pain and eyes strain	(Esposito et al., 2014)
15	Mental load	The load of the task itself and associated with task difficulty	(Choi et al., 2014), (Schnotz & Kürschner, 2007)
16	Performance	The level of understanding for the learning task or the level of acquisition for new information	(Choi et al., 2014), (Schnotz & Kürschner, 2007)
17	Mental effort	The amount of efforts to perform a task	(Choi et al., 2014)

2.11 Summary

This chapter illustrated the essential elements within ambience intelligence concepts and how agent principles have been used to design principles for ambient intelligent agents, which provide the reasoning capabilities to support users. Selected literature on ambience intelligence, agent paradigm, agent-based modelling, agent architectures have provided insights for this endeavour. Later, the concepts of human functioning models (formal models) and examples of such models are described and followed by review on companion robots focusing in human-robot interactions and the effect of physical embodiment. This chapter also discussed vital concepts in reading and learning and how these concepts are related to each other. Moreover, the concepts of cognitive load and reading performance during demanding reading task, and in other domains, have been discussed in detail. It includes detailed discussion on related theories and models of cognitive load and its implication towards this study.

CHAPTER THREE
METHODOLOGY

3.1 Introduction

This chapter presents the research methodology that is used to carry on this study. The methodology was made to answer all the four research questions that were formulated in Chapter One. The research framework of this study is discussed in Section 3.2. All sections from Section 3.3 to 3.7 discuss research activities that were carried out within the methodology framework. Finally, Section 3.8 summarizes this chapter.

3.2 Research Framework

In this section, all standard elements are presented. The research methodology framework based on Design Science Research Process (DSRP) (Peffers et al., 2006), Agent-Based Modelling (ABM) (Drogoul, Vanbergue, & Meurisse, 2003; Nikolic & Ghorbani, 2011), and Ambient Agent Framework (AAF) (Bosse, Hoogendoorn, Klein, Van Lambalgen et al., 2011) is discussed. The framework is divided into five phases, namely; (1) problem identification and motivation, (2) objectives for the solution, (3) design and development, (4) demonstration, and (5) evaluation. These phases are illustrated in Figure 3.1 where each phase has different activities. The details of each phase are illustrated in the following sections (from Section 3.3 to 3.7).

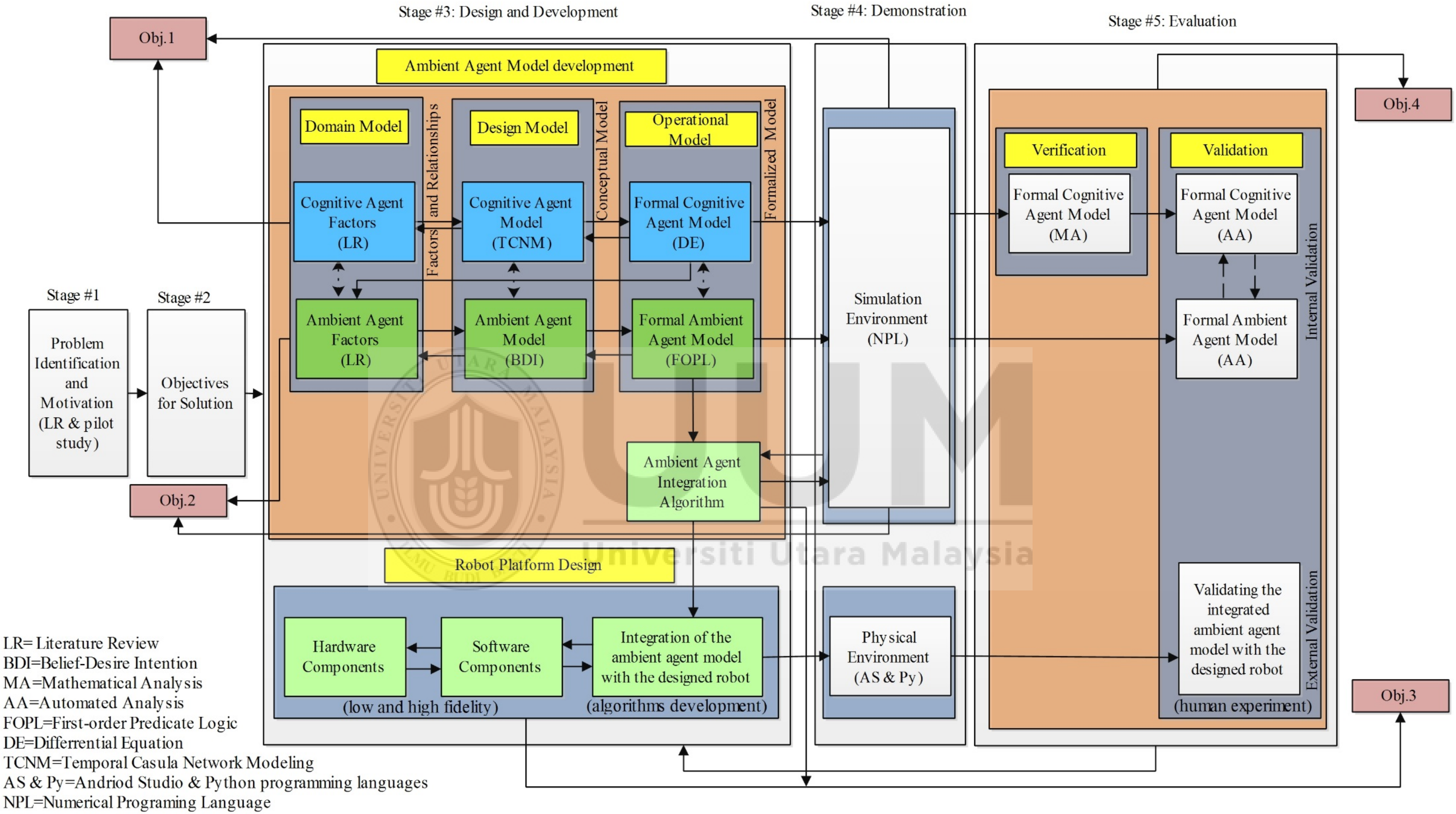

Figure 3.1. Framework of the Research Methodology

3.3 Problem Identification and Motivation

The research problem was established after reviewing the literature of human behaviour, cognitive models, and intelligent applications to support humans in a knowledgeable manner. Moreover, a pilot study was conducted to consolidate the identified problem and determine the most preferred artefact to be used as a medium to support readers. One of the important findings of this phase is the increment of cognitive load and its negative ramifications are the key reason that reduces performance in solving assigned tasks (e.g., demanding tasks). Consequently, the development of a cognitive agent model to comprehend cognitive and physical states of humans and its integration with an ambient agent model framework is a crucial to assist individuals in reducing the negative consequences of high load. Later, it yields better results in terms of improving performance for particular demanding tasks. Figure 3.2 portrays how the research problem was identified.

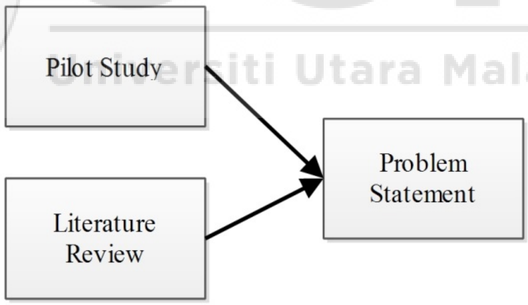

Figure 3.2. Problem Identification

Apart from the pilot study, Figure 3.2 depicts that extensive research works have been reviewed to identify the research problem and design its solution. This activity covers both theoretical and practical aspects from different fields such as Ambient Agent-Based Models (AABM), Companion Robotic (CR), and Cognitive Load (CL) with reading and learning domain.

3.4 Objectives of the Solution

The main objective in this study is to develop an ambient agent model to be integrated as core foundations in designing a reading smart companion robot. To attain this, a human functioning model of cognitive load and reading performance within the scope of reading and learning is developed as a basis to provide an analytical reasoning tool for an ambient agent model (as explained throughout Chapter Four). Furthermore, this model is integrated into a reading companion robot for a human experiments stage. Next section provides important steps on how the model was developed.

3.5 Design and Development

This phase is dedicated on the procedures to be followed in designing a companion robot based on ambient agent models that incorporate human-functioning models as a core reasoning engine. Specifically, it focuses on designing; (1) a cognitive agent model of cognitive load and reading performance, (2) an ambient agent model based on the designed cognitive agent model, (3) a reading companion robot, and (4) an integration algorithm to integrate the designed ambient agent model into the reading companion robot. Figure 3.3 presents the integration between the outcomes from this phase. The required activities to design all components from Figure 3.3 are described in Section 3.5.1, 3.5.2 and 3.5.3. The outcomes from this phase describe the main objectives as covered in Chapter One.

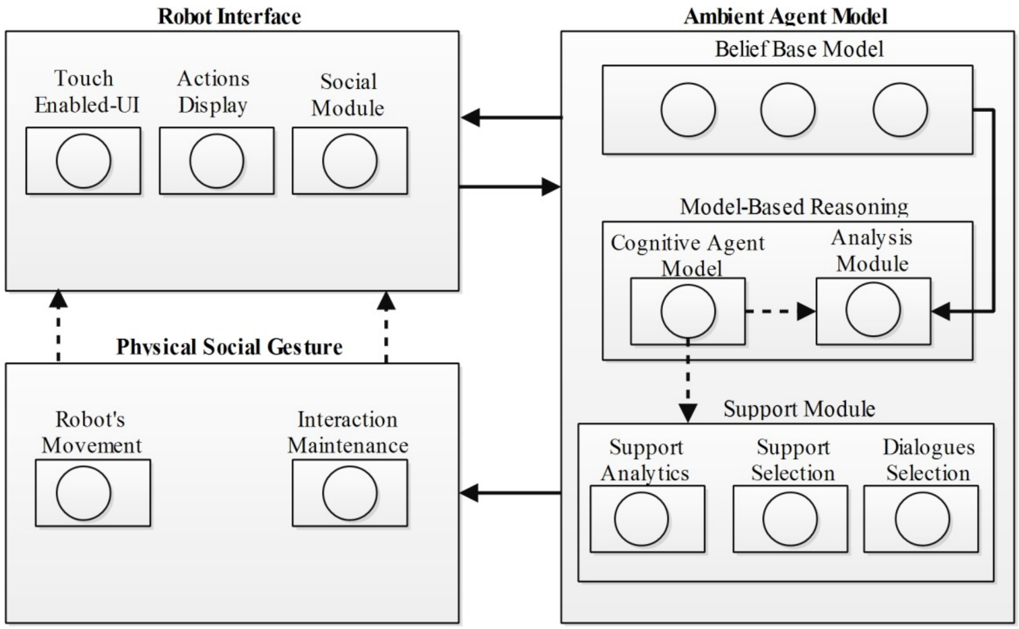

Figure 3.3. A Generic Design of an Ambient Agent Model Integration into a Reading Companion Robot

Figure 3.3 depicts three main components with their integration to serve as a building block in designing a reading companion robot. These components are; (1) ambient agent model, (2) robot interface, and (3) physical social gestures. Note here, the solid arrows indicate information exchange between components (data flow) and the dotted arrows represent the integration process. The comprehensive explanations about these components will be covered from Chapter Four to Chapter Six.

3.5.1 Cognitive Agent Model Design

This section discusses the overall steps to design a cognitive agent model based on an agent-based model simulation methodology (based on Drogoul et al. (2003) and Nikolic and Ghorbani (2011)). The detailed outcomes include domain model, design model, and operational model as explained in next sections.

Domain Model

The domain model pays attention on determining related factors to the relationships between cognitive load and reading performance. These inter-related factors are used to construct the proposed cognitive agent model. Relevant literatures in the domain of cognitive load and reading performance provide detailed insights pertinent to the interplays between all factors and its processes. The reviewing process is conducted by using various literature databases such as Elsevier, IEEE Explore, Springer, Scopus, and Web of Science.

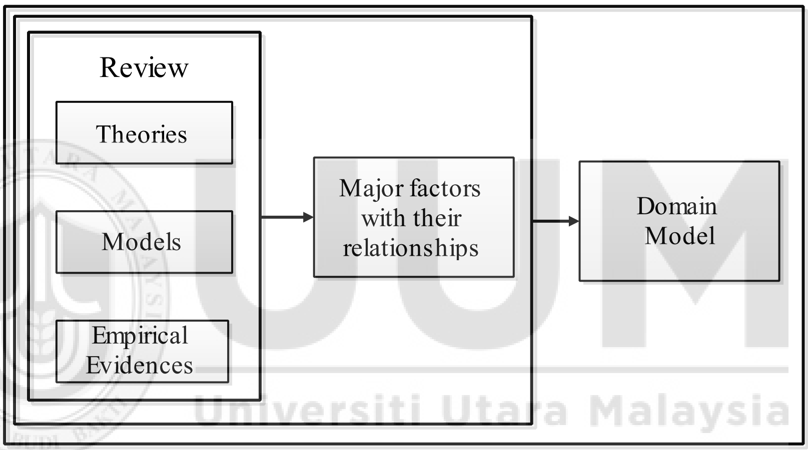

Figure 3.4. Domain Model Development Activities

Figure 3.4 illustrates the undertaken activities for the reviewing process. The outcomes from this step (i.e., factors, interplays, and its relationships) are presented in Chapter Four.

Design Model

The design phase represents a conceptual construct (factors and its relationships) to explain mechanism of an observed phenomenon using a *Network Oriented Modelling* approach. This approach takes concepts in a causal network and its interaction as a basis for complex processes conceptualization and structuring (Treur, 2017a). This modelling approach provides a conceptual tool to represent interconnected complex processes in a structural, intuitive, and easily visualizable manner. Also, this approach incorporates temporal dynamics of the observed system.

Due to its multifaceted ability in modelling complex processes, a large number of successful studies has been used this approach to model the dynamic of psychological, cognitive, and social behaviours (Formolo, van Ments, & Treur, 2017; van den Beukel, Goos, & Treur, 2017). Figure 3.5 illustrates the conceptualization process within a *Network Oriented Modelling* approach. In Figure 3.5, there are two relationships are presented, namely, instantaneous (white node) and temporal relationships (dark grey node). The instantaneous relationship explains the direct impact towards states and its interplays while the temporal relationship often related to the accumulated effects from the previous contributions of the observed function.

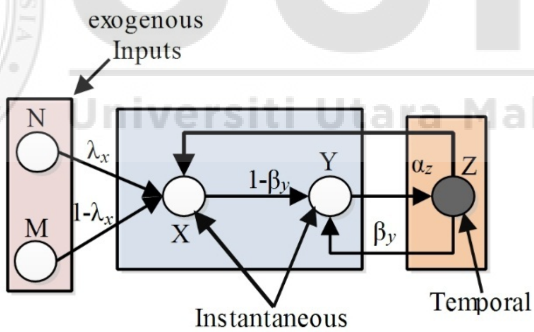

Figure 3.5. Temporal Causal Graph in Network Oriented Modelling

Thus, due to the explained advantages of the *Network Oriented Modelling,* this approach is selected to visualize the conceptual model of cognitive load and reading performance. The outcome from this step is presented in Chapter Four.

Operational Model

In this step, the obtained conceptual model from previous step (design model) is formalized using a set of differential equations. In other words, the conceptual representation of the model (i.e., graphical representation) is transformed into a numerical representation as a basis for simulation and mathematical analysis. Each node was designed to hold values ranging from 0 (low) to 1 (high). Using a toy model, the instantaneous relationships are formalized in the following manner:

For example, from Figure 3.5, *Y* can be formalized as follows:

$$Y(t) = \beta_y . Z(t) + (1 - \beta_y) . X(t) \quad (1)$$

First, from Eq.1, parameter β_y is used to regulate a contribution rate between *X*(*t*) and *Z*(*t*). In this case, when $\beta_y = 0.8$, it means the function *Z*(*t*) contributes up to 80 percent towards the overall value (with the remaining 20 percent contributions from the function *X*(*t*)). Next, the temporal relationships (e.g., Z(*t*) from Figure 3.5) are specified in the following manner:

$$Z(t + \delta t) = Z(t) + \alpha_z . (Y(t) - Z(t)) . Z(t) . (1 - Z(t)) . \delta t \quad (2)$$

From Eq.2, it is important to mention the change in *Z*(*t*) is measured in a time interval between *t* and *t*+δ*t*. This change is determined by the continuation factor $(Y(t) - Z(t))$, as α_z is a speed change parameter. Moreover, as this model is designed to hold values ranging from 0 to 1, new $Z(t)$ and (1- $Z(t)$) functions are introduced to regulate possible boundary values of *Z*(*t*). These effects of these functions are shown in Figure 3.6.

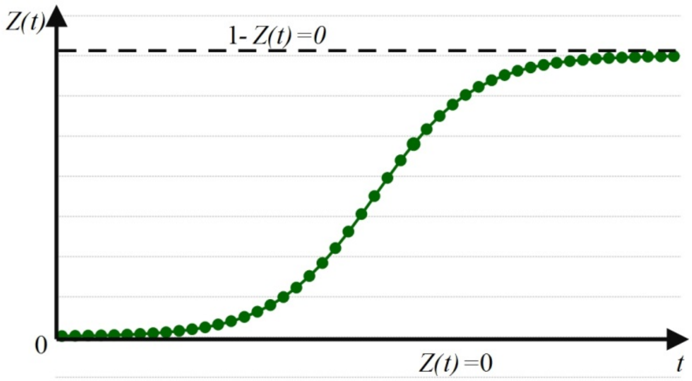

Figure 3.6. The Boundary Specifications

In a summary, this phase is conducted to formalize the conceptual cognitive agent model of cognitive load and reading performance. Later, this formal model is constructed for simulation purposes. The developed and simulated cognitive agent model achieves the first objective of this study as stated in Chapter One.

3.5.2 Ambient Agent Model Design

The obtained cognitive agent model from the previous section is used as the focal element in designing an ambient agent model as in Figure 3.1. An agent-based simulation methodology is used to construct this model.

Domain Model

Within an ambient agent model design, the domain model focuses on identifying the essential support factors (i.e., support actions) that can be used to help in the pressure of cognitive load and its ramifications based on the developed cognitive agent model. Later, those support constructs will be combined with the cognitive agent model to build an ambient agent model. Important theories and empirical evidences from the literature provide major information to construct this model. Chapter Five covers thorough discussion related to this model.

Design Model

The design model contributes towards the development of a conceptual ambient agent model based on the underlying cognitive agent model (Bosse, Hoogendoorn, Klein, van Lambalgen et al., 2011). By integrating human functioning models (or cognitive agent models) within ambient agent application models, the developed intelligent applications will be able to reason and understand the overall process within the observed phenomenon (as in Figure 3.3; analysis module and support module encapsulate this human-like understandings). Thus, such human-like understanding abilities enable a digital system to perform actions in a more informed and to show more human-like behaviour in interaction with users (Klein et al., 2017).

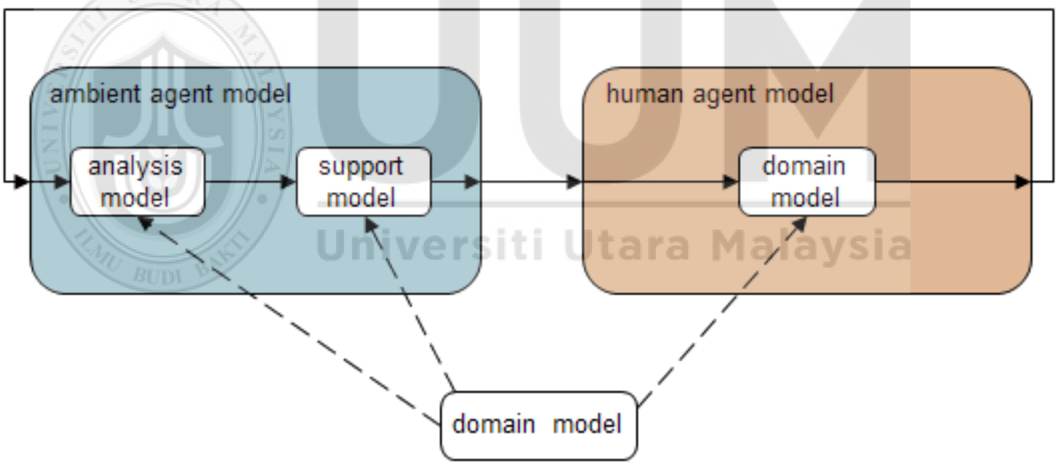

Figure 3.7. Integration of Domain Model within Ambient Agent Model

For further examinations, the developed domain model (i.e., cognitive agent model of cognitive load and reading performance) is integrated through both *analysis model* and *support model* (as in Figure 3.7). Here, the solid arrows indicate information exchange between processes (data flow) and the dotted arrows represent the integration process.

Analysis Model

This model aims to perform analysis of the reader's cognitive states and processes by model-based reasoning approach grounded on observations and the domain model. This model is separated into *belief base* and *analysis* models, and more about these models is covered in Chapter Five.

Support Model

This model generates support actions for the readers by analysing results from the model-based reasoning through a set of observations and information relayed by the domain model. Furthermore, it is worth mentioning that this integration among the three models (i.e., *domain model*, *analysis model*, and *support model*) has been accomplished based on a Belief-Desire-Intention concept (BDI) (Aziz, Klein, & Treur, 2010). Details on BDI concept are covered in Section 2.3.2.

To understand the underlying concept of BDI, a simple example of an ambient agent application model, using the domain model presented in Figure 3.5, is designed (as shown in Figure 3.8). This model uses the domain model results to perform analysis through a set of observations in generating *beliefs* about reasons (i.e., a belief about *M*). The analysis can be achieved by performing an analysis from a domain model where desires to support *Z* are generated. During this stage, both beliefs and desires are combined to produce intentions to support *Z*. Next, the domain model will be used as a reference (e.g., evaluation purposes).

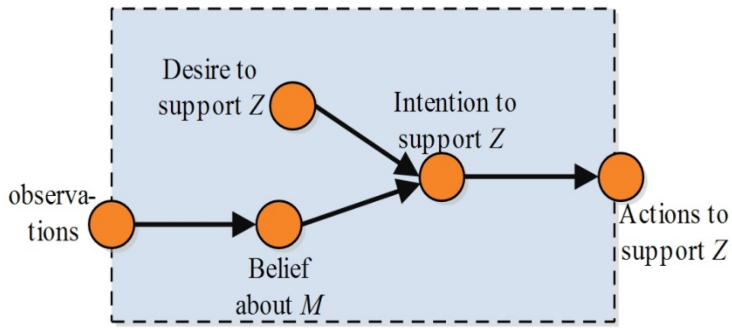

Figure 3.8. Basic Concept of an Ambient Agent Model

As a result from this step, a conceptual design of an ambient agent model of cognitive load and reading performance is developed.

Operational Model

The operational model can be derived by formalizing a conceptual design of an ambient agent application model using *First-Order Predicate Logic* (FOPL) or Predicate Calculus. The ontologies and its specifications of the model are the outcomes from this stage. For example, the ontologies of agent's belief about *M,* agent's intention to support *Z,* and agent's desire to support *Z,* from Figure 3.8, can be specified as follows:

belief (X: AGENT, M (L: LEVEL))
desire(X: AGENT, SUPPORT(*Z))*
intention(X: AGENT, SUPPORT(Z))

Note here, the sort of LEVEL is specified as follows:

$$\text{LEVEL:} = \{\text{high, medium, low}\}$$

By using the BDI approach based on designed ontologies, the specification rules can be generated to determine the agent's actions selection. For instance, the specification about generating intention to support *Z* is formalized as follows.

GIN: Generating intention to support *Z*

If the ambient agent believes that the level of M is high and it has desire to support Z, then it leads to the ambient agent will have an intention to provide support to Z.

$$\text{belief(X: AGENT, M(HIGH))} \wedge \text{desire(X: AGENT, SUPPORT(Z))} \twoheadrightarrow \text{intention(X: AGENT, SUPPORT(Z))}$$

The same given concept is implemented to generate an executable ambient agent model of cognitive load and reading performance. The developed ambient agent model accomplishes the second objective of the study (as stated in Chapter One).

Ambient Agent Integration Algorithms

Upon completion of design, simulation and evaluation process of an ambient agent model (as presented in Figure 3.1), this model is transformed into a set of algorithms. These algorithms are divided into six main modules, namely; (1) physical environment module, (2) monitoring module, (3) evaluation module, (4) persistence module, (5) exhaustion module, and (6) cognitive load module. These algorithms serve as an underlying analytical tool in monitoring and analysing reader's performance to generate suitable support actions. The notations used to develop the algorithms are inspired by Cormen (2009). Based on these algorithms, the proposed reading companion robot activities are specified. Specifically, these algorithms permit the companion robot based on its software engine (the ambient agent model) to select appropriate support actions, and dialogues (e.g., engagement, evaluation, and support dialogues). Also, they act as an instrument to maintain the human-like social interactions processes for both human-robot interaction and its mechanical engagements (See Figure 3.3). Detailed discussion about the integration algorithms development can be found in Section 5.6 (Chapter Five).

3.5.3 Robot Platform Design

Parallel to the development of an ambient agent model of cognitive load and reading performance, the underlying principles of designing a companion robot that cover both software and hardware are explored (i.e., robot appearances and human-robot interaction criteria). As a first step towards designing a reading companion robot, a pilot study was conducted among 100 Universiti Utara Malaysia students from different academic programmes and backgrounds. The convenience sampling was used to determine targeted respondents based on a suggested protocol established by Ritchie, Lewis, Nicholls, & Ormston (2013). The results have shown that a table lamp object is chosen as a favoured medium over table fan, clock, pen holder, and mug. Therefore, a table lamp is opted for a physical representation of a reading companion robot (Mohammed, Aziz, & Ahmad, 2015).

Regarding the software components, these integration algorithms provide an automated reasoning engine to control the entire analytical functionalities of the robot. As for the physical component of the companion robot, it includes; (1) a microcontroller (Raspberry Pi) to connect the different hardware components, (2) Android tablet to execute the computational process (i.e., to execute the integration algorithms), and (3) servo and DC motors to control the robot's movement (powered by motors driver). The complete explanations about the robotic and its platform design are presented in Chapter Five. Note here, the integration algorithms along with the robot platform design achieve the third objective of the study.

3.6 Demonstration

This phase is divided into two parts; simulation and physical environment. The first part simulates the behaviours of operational models of the cognitive agent model and its ambient agent model, while the second part demonstrates the functionality test of the designed companion reading robot. Both Section 3.6.1 and 3.6.2 present comprehensive explanations about simulation and physical environment activities.

3.6.1 Simulation

In this section, the undertaken activities in simulating the developed models were presented as follows.

Cognitive Agent Model Simulation

First, the obtained cognitive agent model is simulated to understand the dynamic process within the domain problem. By simulating this model, it becomes easier to evaluate the correctness of the model and understand how the real-world behaviour process occurs. This stage has been achieved by assigning different values ranging between zero (low) and one (high) as the exogenous (external) inputs to the model. Moreover, a numerical simulation environment such as Matlab is used due its computational efficiency in handling a large volume of simulation traces for human cognitive behaviours (Aziz & Klein, 2011; Adegoke, Aziz, & Yusof, 2015). Also, for a clearer understanding about the model behaviours, a set of simulation experiments were conducted to evaluate possible variation of initial temporal values as discussed in Chapter Four (Section 4.4). For example, the conceptual causal network model (as in Figure 3.5) is simulated in numerical processing environment (e.g. Matlab) to get deeper insights about the dynamics of instantaneous and temporal relationships. The example of generated simulation results is presented in Figure 3.9.

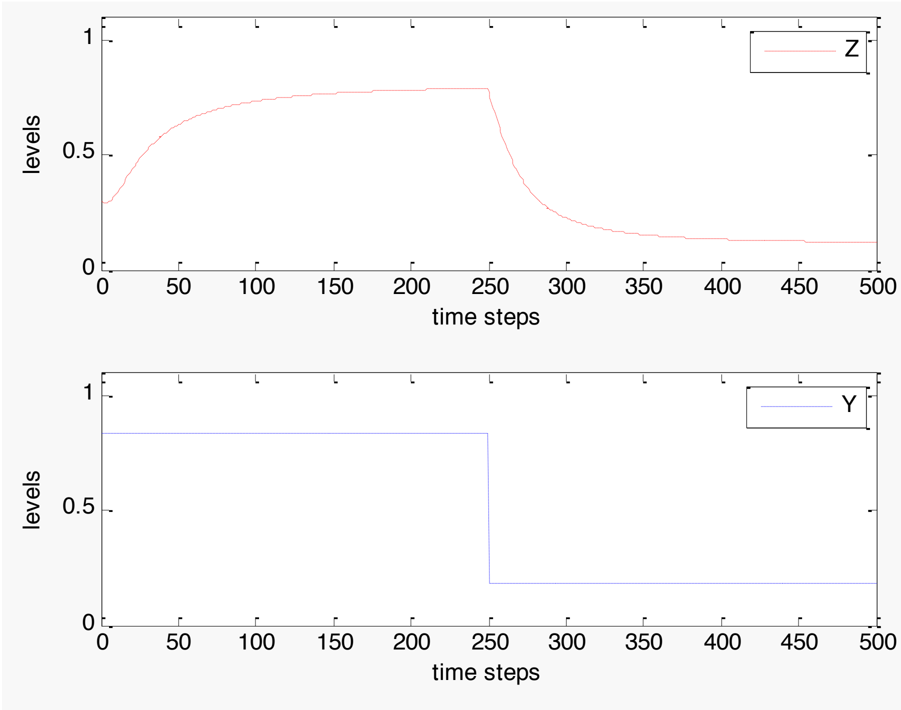

Figure 3.9. Examples of Instantaneous and Temporal Simulation Traces

According to Figure 3.9, it can be seen clearly that the temporal value of *Z*(*t*) is positively correlated to its precursor *Y*(*t*). It means either positive or negative constant exposure towards *Y* condition causes a delayed impact to generate an overall temporal value for *Z* within observable periods of *t* and $t+\Delta t$. In this study, the obtained outcome from this stage is a simulated model that explains the real-world behaviour of the cognitive load and reading performance during demanding reading tasks (i.e., covered in Chapter Six).

Ambient Agent Model Simulation

In this stage, the developed ambient agent model is simulated to get clear insights on the support actions behaviours within the designed model using a temporal specification language called LEADSTO (Bosse, Jonker, van Der Meij, & Treur, 2005; Bosse, Jonker, van der Meij, Sharpanskykh, & Treur, 2009). The executable temporal rules specifications from operational model were used to simulate the ambient agent model. It enables one to model direct temporal relationship between two state properties. The LEADSTO format is defined as follows.

> Let α and β be state properties of the form 'conjunction of atoms or negations of atoms', and *e, f, g, h* non-negative real numbers. In the LEADSTO language the notation $\alpha \twoheadrightarrow_{e, f, g, h} \beta$, means:
>
> *If state property* α *holds for a certain time interval with duration g, then after some delay (between e and f) state property* β *will hold for a certain time interval of length h*

The timing relationship between the state properties is depicted in Figure 3.10. In addition, the LEADSTO representation also holds a temporal trace γ, denoted by:

$$\forall t1: [\forall t\ [t1-g \leq t < t1 \Rightarrow state(\gamma, t) \models \alpha\ ]$$
$$\Rightarrow \exists d\ [e \leq d \leq f\ \&\ \forall t'\ [t1+d \leq t' < t1+d+h$$
$$\Rightarrow state\ (\gamma, t') \models \beta\ ]$$

Figure 3.10 summarizes the temporal representation of the ambient agent model.

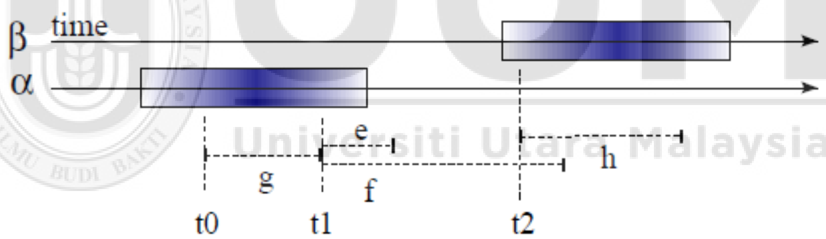

Figure 3.10. The LEADSTO Timing Relationships

The generated temporal rules specifications in Section 3.5.2 were executed in LEADSTO and the results are depicted in Figure 3.11.

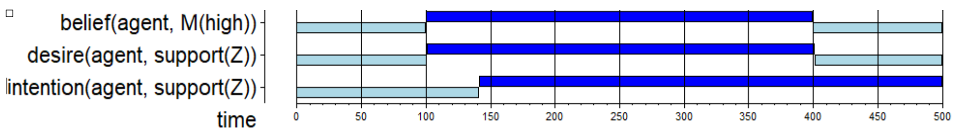

Figure 3.11. An Example of LEADSTO Simulation Traces

This simulation trace visualizes the designed ambient agent behaviour. It shows if the ambient agent believes that the level of *M* is high and it has desire to support *Z*, then the ambient agent will have an intention to provide support to *Z*. This concept was used to simulate the behaviour of the developed ambient agent. More discussions about the simulation results can be found in Chapter Five (Section 5.5).

3.6.2 Physical Environment

In this section, the developed companion robot is operated, and several functionality tests were conducted to ensure the robot free from any possible operational errors. To attain this, an Android Virtual Device (AVD) (emulator environment) in Android studio and Python editor IDE (Integrated Development Environment) of Raspberry Pi were used. Further explanation about this process is presented in Chapter Five (Section 5.10).

3.7 Evaluation

Once the simulation models and robot development were completed, the next step was to evaluate the developed ambient agent model and its integration with the robot. Figure 3.12 summarizes the hierarchy of the evaluation activities in this study. The extensive details about the evaluation techniques are discussed in the next sections (Section 3.7.1 and 3.7.2). Note here, all the evaluation results in this study serve to achieve the fourth objective of this study.

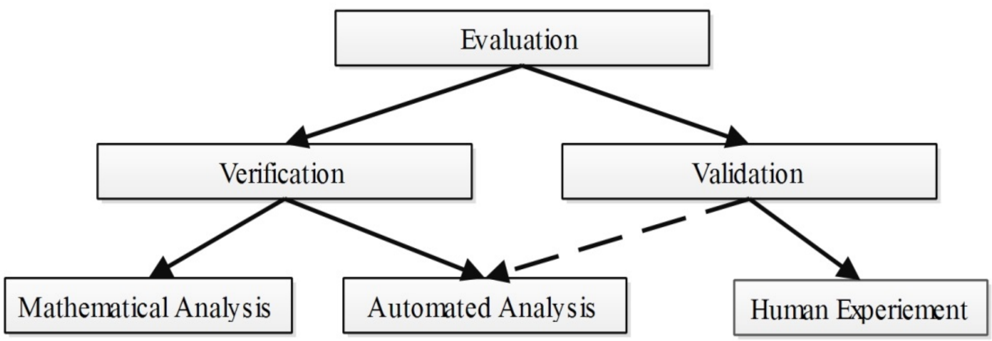

Figure 3.12. Evaluation Phase Activities

From Figure 3.12, it is also possible to consider the automated analysis approach as a method to perform validation process (i.e., internal validation). It is due to its ability to make use of empirical results from previous experiments of selected developed models or domain (Treur, 2016).

3.7.1 Verification

In agent-based modelling, verification is the process of ensuring that the conceptual descriptions and model are correctly implemented. In other words, it aims at showing the degree of correctness of the representation of the real target system as intended by the study (Voogd, 2016). Moreover, this process is performed to improve important understanding of real world behaviour and computational models, estimate values of the parameters, and evaluate system performance (Aziz, Ahmad, ChePa, & Yusof, 2013).

In a bid to find agent based model verification methods from the literature, there are two widely-used approaches to ensure the correctness of the intended models, namely; *mathematical analysis* and *automated logical analysis* (Bosse, 2005; Bosse, Jonker, Meij, & Treur, 2006; Bosse et al., 2009; Bosse, Pontier, & Treur, 2010). A more intuitive explanation on these approaches can be seen in Figure 3.13. The verification process using mathematical analysis starts from the specifications of the real-world behaviours to the conceptual model design and its implementation (i.e., rightwards arrows). Through this mechanism, models can be checked if it has been correctly developed. The main goal is to show the simulated models are adhered to the specification.

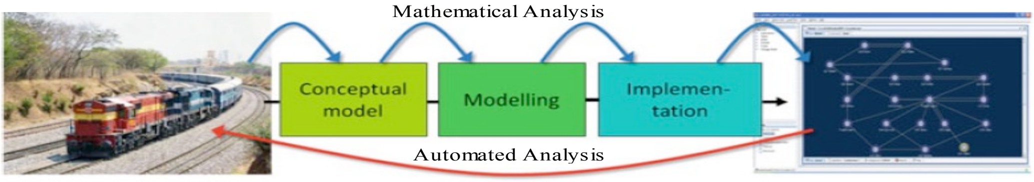

Figure 3.13. General Use of Mathematical and Automated Analysis

The automated analysis in Figure 3.13 is used to ensure the internal validity of the obtained models. This approach uses secondary source (e.g. previous empirical experiments) of information about real world processes. Therefore, this approach can be considered, for both methods, to verify and also to internally validate the models (Treur, 2016). Figure 3.14 summarizes the verification processes used in this study.

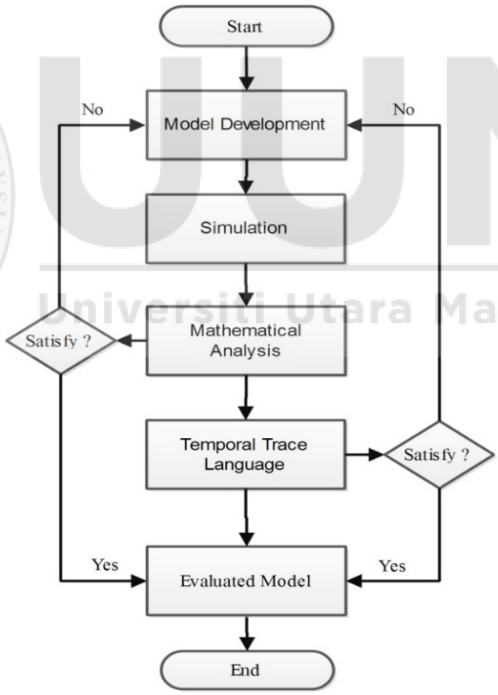

Figure 3.14. Verification Processes

3.7.1.1 Mathematical Analysis

Mathematical analysis can be an important instrument in the development of ambient intelligence applications. If the formalization of such a model is expressed in mathematical formulae, performing a mathematical analysis can provide insight into several important properties such as internal verification (i.e. for checking whether the model behaves consistently, both in relation to the model specification and the abstraction of reality that the model aims at) (Treur, 2016d). Equilibria analysis is used in mathematical verification process. It is used to describe situations in models where the values (continuous) approach a limit under certain conditions and stabilize (Korn & Korn, 2000). It means if the dynamics of a system is described by a differential equation, then equilibria can be estimated by setting a derivative (or all derivatives) to zero.

One important note that an equilibria condition(s) is considered stable if the system always returns to it after disturbances (Treur, 2016a). These stabilized points from the mathematical analysis can be used for verifying the model by checking them against the values observed in simulation experiments. For example, the autonomous equation from Section 3.5.1:

$$Z(t+\ \delta\ t) = Z(t) +\ \alpha_{y}.\big(Y(t) - Z(t)\big).Z(t).\big(1 - Z(t)\big).\ \delta\ t$$

can be rewritten as (assuming α_{y} is nonzero):

$$dZ(t)\ /dt = Z'(t) = Y - Z$$

The equilibria or stable points of this differential equation are the root of this equation. It means as follows.

$$Z'(t) = 0$$

Consequently, the stable point can be found when,

$$Y = Z$$

As such, the existence of reasonable equilibria is also an indication for the correctness of the model (Ayasun, Fischl, Vallieu, Braun, & Cadırlı, 2007). The visualization of these stable points is shown in Figure 3.15. It can be concluded that the model formalization is correct as it exhibits reasonable equilibrium points when *Y* is equal to *Z*.

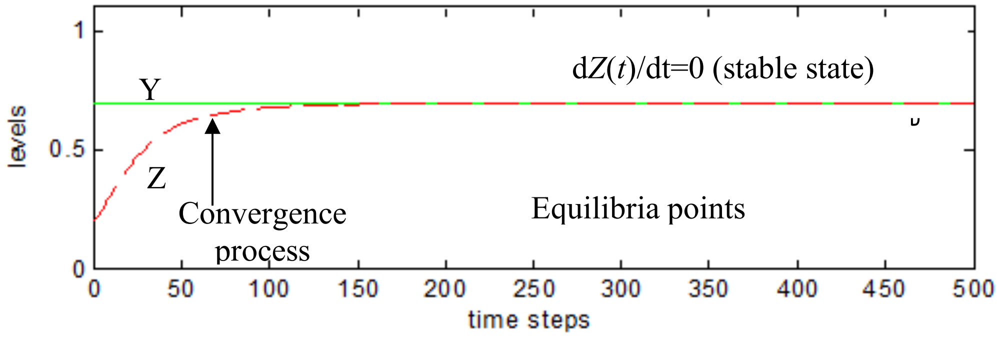

Figure 3.15. Equilibrium Condition in Stability Analysis

The evaluation process for the proposed cognitive agent model (i.e., using stability analysis) is discussed in Chapter Six (Section 6.1.1).

3.7.1.2 Automated Analysis (Internal Validity)

Logical (or automated) analysis can be as an essential instrument to confirm that the obtained results of an agent modelling are consistent with the literature and previous empirical findings (Bosse et al., 2009; Sharpanskykh & Treur, 2010a; Hoogendoorn, Jaffry, van Maanen, & Treur, 2014). The dynamic properties of the cognitive agent model can be checked to verify whether the model yields outcomes that are adhere with the previous empirical findings. Thus, it gives clear insights on the correctness of the model. In the same vein, the obtained results of the ambient agent model can also be evaluated using this approach to verify the ambient agent model and the given support.

To attain this, the Temporal Trace Language (TTL) is used to perform an automated verification for specified (formalized) properties (obtained from empirical literature) against a set of generated simulation traces. This language allows formal specification and analysis of both qualitative and quantitative dynamic properties (Bosse et al., 2006). TTL is designed on atoms, to represent the states, traces, and time properties. This relationship can be presented as a *state(γ, t, output(R))* |= *p*, it means that state property *p* is true at the output of role *R* in the state of trace at time point *t*. Based on that concept, the dynamic properties can be formulated using a sorted predicate logic approach. TTL uses a piece of software called TTL checker tool to check whether a specified property holds for particular traces or not.

This tool takes a TTL property in the form of a set of traces (for example, Matlab, C++, or LEADSTO simulation traces), and generates an answer as a 'yes' (in case the property holds for all traces in the set) or a 'no' (in case the property fails for at least one of the traces). For example, the simulation result from Figure 3.11 is used to check the state property *Z*. The obtained Matlab traces (VP1) are used as an input to TTL checker. The TTL property (VP1) of *Z* is specified accordingly to represent changes in *Y* (i.e., case="high"). This property holds true and the automated logical verification representation is as follows.

VP1 ≡ ∀ γ : TRACE, t1, t2: TIME, D1, D2, R1, R2: REAL
[state(γ , t1)|= has_value(Y, R1) &
state(γ , t2)|= has_value (Y, R2) &
state(γ , t1)|= has_value (Z,D1) &
state(γ , t2)|= has_value (Z,D2) &
t2 > t1 & R2 ≥ R1] ⇒ D2 ≥ D1

The automated verification results of the developed cognitive agent model are presented in Chapter Six (Section 6.1.2).

3.7.2 Validation

Overall, the validation part aims at evaluating the reading companion robot prototype using user-centred approach where users participated directly to evaluate the robot. In this study, the effects of model's reasoning ability or given support have been investigated. Hence, the main goal of this validation phase is divided into two purposes. First, it aims to evaluate the user's attitude and perception towards reading companion robot (e.g., its usability). Second, it measures the effect of using the designed robot (e.g., reduce or control the cognitive load level). To attain this goal, both quantitative and qualitative approaches were used through an experimental study with undergraduate students from School of Computing, Universiti Utara Malaysia who have completed their Data Structure and Algorithm Analysis subject in a previous semester. The data collection instruments were constructed based on survey research approach that used closed-ended questions and semi-structured interview. This survey is consisted of five sections (A-F), where section A focused on demographic information of the respondents, while section B dealt with the system usability questionnaires. The usability questionnaire is based on the suggestion from (Brooke, 1996; Bangor, Kortum, & Miller, 2008; Lewis & Sauro, 2017). Ten different questions were used in the usability questionnaire using the 7-points Likert scale measurement. The example of these scales is as follows.

Strongly Disagre	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Strongly Agree**

In Sections C and D, it measures overall user's attitude and perception towards the usage of a reading companion robot. In details, Section C includes; (1) perceived likeability, (2) perceived intelligence, and (3) perceived animacy. These measurements are developed based on 7-points semantic differential scales (adopted from Bartneck, Kulić, Croft, & Zoghbi (2009)). While, Section D includes; (1) perceived sociability, (2) perceived usefulness, and (3) perceived social presence. These measurements are developed based on 7-points Likert scales (adopted from Heerink, Krose, Evers, & Wielinga, 2009; Heerink, Kröse, Evers, & Wielinga 2010).

It is vital to remark that both of Likert scale and semantic differential scales are rating scales to measure respondent's perception and their statistical analysis is identical. However, in semantic differential scales, the respondents were asked to indicate their position on a scale between two bipolar words, (see Figure 3.16, top). However, in Likert scales (see Figure 3.16, bottom), respondents were asked to respond to a stem, often in the form of a statement, such as "I like the reading companion robot". The scale is frequently anchored with choices of "agree"–"disagree" or "like"–"dislike". The detailed implementation of this notion can be found in Bartneck et al., (2009).

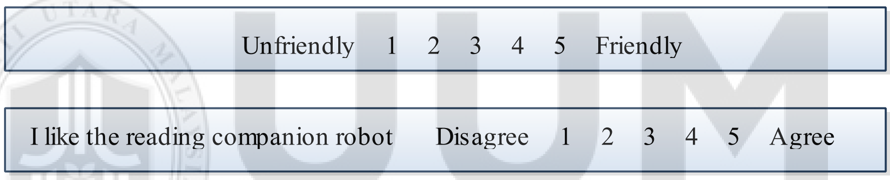

Figure 3.16. Examples of a Semantic Differential Scale (top) and a Likert Scale (bottom).

Furthermore, Section E is used to measure the overall cognitive load encountered by readers while solving a reading demanding task. In this study, the cognitive load level is measured by utilizing a question addressing the level of difficulty for the given tasks based on a 7-point Likert scale ranging from 1 (extremely easy) to 7 (extremely difficult). This is adopted from Joseph (2013); Schmeck, Opfermann, van Gog, Paas, and Leutner (2015) where respondents were asked to rate their perception about assigned task with respect to its difficulty level. Lastly, Section F was used to measure quantitative indicators in *Desire to Continue* using the system, *Satisfaction with the Support* given while using the robot, and *Motivation* where respondents are asked to rate how the robot can motivate them when performing demanding reading tasks.

These instruments were developed by following the concepts from Bickmore, Caruso, Clough-Gorr, and Heeren (2005) where a single item on 7-points semantic differential scale is used to get respondents' rating. Moreover, these questions are used for further discussion with the respondents using a loosely-structured interview (or semi-structured interview) to get insights on regarding their interaction with the robot (Kidd, 2008). Table 3.1 summarizes all the aforesaid instruments. Noted here, they are used at different time frame during the experimental study. The details of validation process can be found in Appendix B.

Table 3.1

The Measurement Instruments Used in the Study

Section	Measured Concept	Technique	Reference
A	Respondents' Background	Multiple choices question	
B	System Usability	7-points Likert scale	(Brooke, 1996; Bangor, Kortum, & Miller, 2008; Lewis & Sauro, 2017)
C & D	User's attitude and Perception	7-points semantic differential scale	(Bartneck, Kulić, Croft, & Zoghbi; 2009; Heerink, Krose, Evers, & Wielinga, 2009; Heerink, Kröse, Evers, & Wielinga, 2010)
E	Cognitive Load Level	7-points Likert scale	(Joseph, 2013; Schmeck et al., 2015)
F	Desire to continue using the system, Satisfaction with the support given, and motivation	7-points semantic differential scale/ semi-structured interview	(Bickmore, Caruso, Clough-Gorr, & Heeren, 2005)

3.7.2.1 Pilot-Test Study

Prior to the main experiment, a pilot test was conducted as a precursor to understand and validate the evaluation instruments. In this study, five undergraduate students from School of Computing, Universiti Utara Malaysia (who completed the Data Structure and Algorithm Analysis subject) were recruited based on voluntarily basis with the help of lecturers. All respondents were introduced to the reading companion robot to evaluate its usability and interviewed to figure out possible technical errors prior to the main study.

Each participant was briefed about the robot functionalities and allowed to use the robot for 15 minutes. This is crucial to get prior human-robot interaction fluency. Later, the participants were asked to use the robot as a reading companion for an hour to support them while solving assigned tasks (selected topics in Data Structure and Analysis of algorithms). During the experiment, an observation analysis was used by the experimenter to capture the participants' experiences about positive or negative aspects of the experimentation procedures. This observation analysis method is adopted from the research work in evaluating human-robot interactions (Svenstrup, Bak, Maler, Andersen, & Jensen, 2008). Furthermore, at the end of the experiment, the questionnaires as presented in Appendix B were disseminated to ensure the validity of the instruments. Chapter Six covers the outcomes from this pilot study.

3.7.2.2 Validation Protocol

The effects of the given support from the designed ambient agent model and measurement of user's attitudes and perceptions towards the reading companion robot can be validated via human experiment. In this experiment, the survey research approach using closed ended questions was used to get related information from the respondents (as described in Section 3.7.2). Furthermore, 27 students were selected from the School of Computing, Universiti Utara Malaysia. Those students have been identified to have poor performances in Data Structure and Algorithm Analysis subject (i.e., students who scored between C- and C+ were selected).

This is to guarantee that all students were selected from a homogenous pool where the impact of possible bias can be eliminated. From the given lists, emails were sent to all selected students (respondents) and a brief introduction about the experiment and the designed reading companion robot was given. Moreover, a consent form was also distributed (as depicted in Appendix A). Only 20 students have decided to join the experiment on voluntarily basis. The purposive sampling technique was chosen as a guideline to select the students. Upon agreement between those students, specific time and venue were determined.

Later, students were grouped equally into two groups (tablet and robot conditions) and they were asked to read and solve the Data Structure and Algorithm Analysis reading task (i.e., Tower of Hanoi puzzle) for an hour. The first group of respondents only used the ***Tablet*** (as presented in Figure 3.17 (a)). The tablet was mounted on a tablet holder. For the second group, the use of ***Robot*** was presented (as in Figure 3.17 (b)) and participants were asked to complete the given similar Data Structure and Algorithm Analysis task (as identical for the tablet platform). This experimental protocol followed the previous experimental studies conducted by Williams, Peters, and Breazeal (2013) and Williams et al. (2014) to evaluate in-car assistant robot (AIDA).

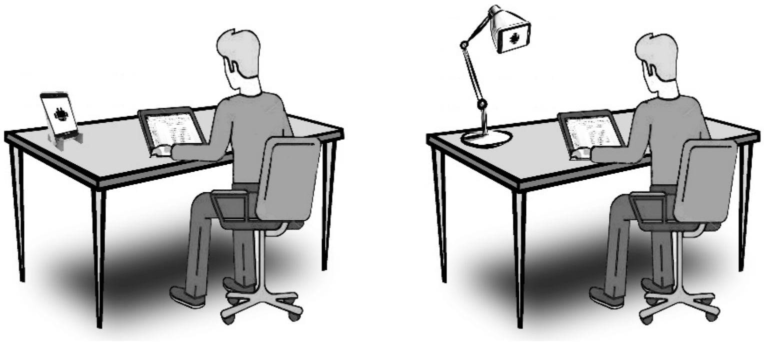

Figure 3.17. The Usage of a Tablet (a) and a Robot (b)

Upon participants' arrival, a basic orientation was given to describe the procedures of the experiment. Later, a demonstration on how to use both tablet and robot (e.g., how to input data using On-Screen Keyboard) was conducted. They were allowed to use the tablet or robot until they feel comfortable or familiar with it. Next, the participants were asked to solve the Data Structure and Algorithm Analysis task for an hour and related ambient agent system is placed next to them.

The experiments were prompted at three specific times to evaluate the cognitive load level (via questionnaire) as in Figure 3.18. After an hour, participants were asked to stop from solving the task and answered the survey questionnaire to measure their attitude and acceptance towards the developed ambient agent system (both *Tablet* and *Robot*) and its usability. Finally, all participants were given light refreshments and a token of appreciation at the end of the experiment. The discussed activities are summarized in Figure 3.18.

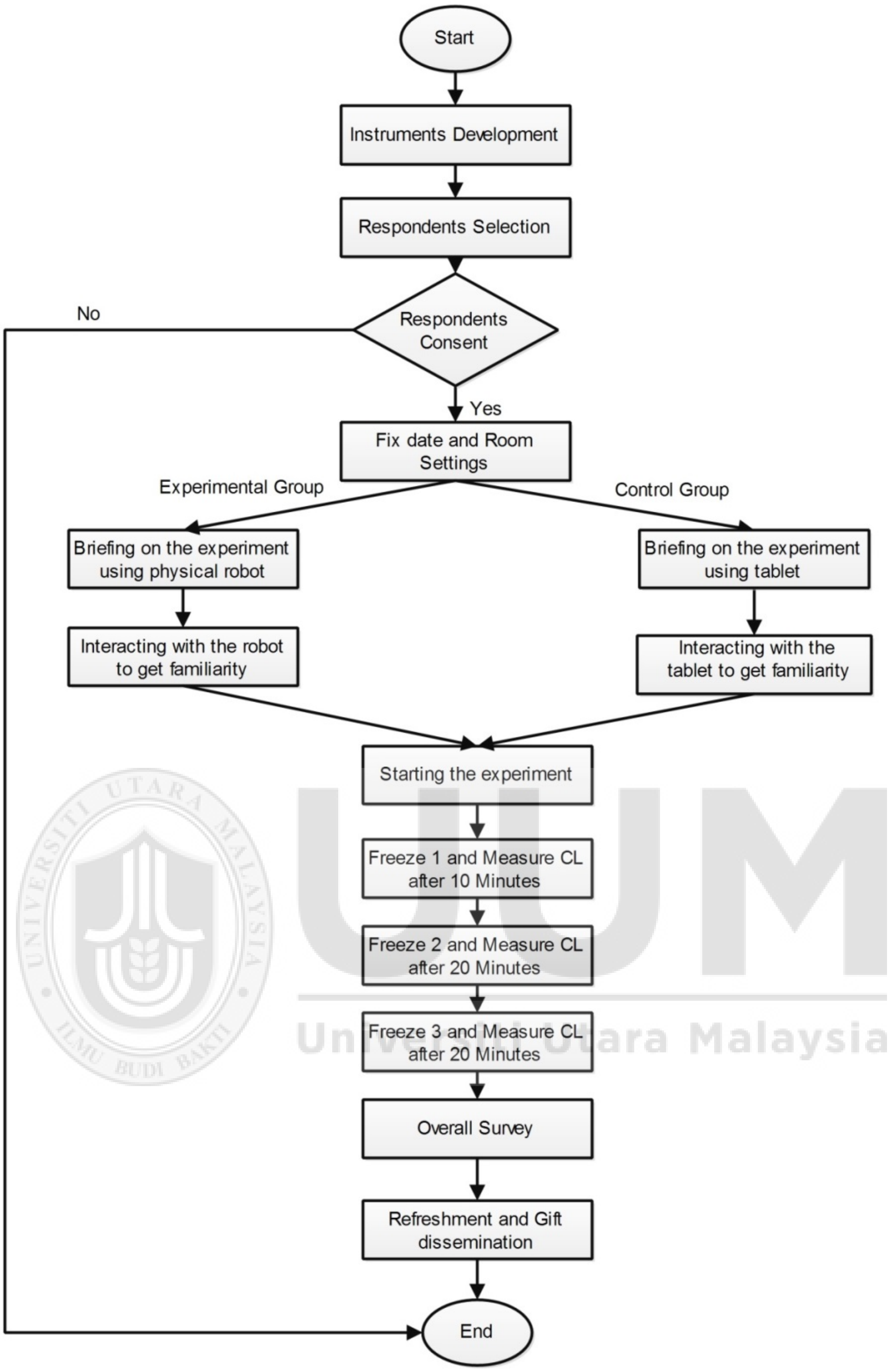

Figure 3.18. Experimental Protocol Activities Flow Chart

3.8 Summary

This chapter explained the study methodology to answer the four research questions as mentioned in Chapter One. The study methodology was adapted based on Design Science Research Process (DSRP) (Peffers et al., 2006), Agent-Based Modelling (ABM) (Drogoul, Vanbergue, & Meurisse, 2003; Nikolic & Ghorbani, 2011), and

Ambient Agent Framework (AAF) (Bosse, Hoogendoorn, Klein, van Lambalgen, et al., 2011). The methodology consists of six phases, namely; problem identification and motivation, objective for the solution, design and development, demonstration, and evaluation. Table 3.2 shows a summary on each phase and all methods or tools that were used to achieve the intended objectives.

Table 3.2

A Summary of Research Methodology Phases

Stage	Method/Tool	Outcome	Objective
Problem identification and motivation	Literature Review and pilot study	Problem statement	
Objective for the solutions	DSRP, ABM, and AAF methodologies to design a Generic model for integrating human-functioning model into a companion robot	A generic model to demonstrate the integration of human-functioning model into a companion robot	Main obj.
Design and development	Literature review, differential equation, symbolic representations, microcontrollers, Android smartphone, and First-Order Logic Predicate Calculus	Factors, concepts of cognitive load and its interplays, ambient agent model, ambient agent integration algorithm, a reading companion robot	Obj. 1,2&3
Demonstration	Matlab, LEADSTO, and Android Studio Platform	Simulated cognitive agent model, simulated ambient agent model with its integration into an agent technology, designed a reading companion robot.	Obj.2 & 3
Evaluation	Mathematical verification (stability analysis), automated validation (TTL), and human experiment	Evaluated models and a reading companion robot	Obj. 4
Communication	Targeting conferences and journals	List of Publications	

CHAPTER FOUR
COGNITIVE AGENT MODEL DEVELOPMENT

This chapter discusses thorough explanations pertinent the design and development of a cognitive agent model. First, the identification of the important factors related to cognitive load and reading performance with its relationships is presented in Section 4.1. Second, the obtained factors with its interplays serve as a building block to design the conceptual design of the cognitive agent model is described in Section 4.2. Later, Section 4.3 explains the formalization processes of the designed cognitive agent model. Moreover, detailed explanations on simulation results of the cognitive agent model are presented in Section 4.4 where different simulation cases using a numerical simulation environment are depicted. Finally, Section 4.5 concludes this chapter.

4.1 Domain Factors and Its Relationships

One of the important steps to develop a cognitive agent model is the identification of related factors with its relationships. In this study, these factors and its relationships are based on intensive literature review and empirical studies as discussed in Chapter Three (Section 3.5.1). The results from this main step have provided twenty-eight (28) important factors related to the underlying principles of Cognitive Load Theory (CLT) (Sweller et al., 2011).

These factors are categorized into exogenous, instantaneous, and temporal factors. The exogenous or external factors are independent factors that form inputs to the model, while instantaneous factors explain the current states of the observed problem. Temporal factors often refer to the accumulative effects due to the delayed contribution. For a further examination on exogenous factors of the cognitive agent model, Table 4.1 outlines a detailed description on selected exogenous factors.

Table 4.1

Exogenous Factors

No.	Concept	Nomenclatures	Description	Reference
1	Reading Task Complexity	*Tc*	Difficult reading task that someone must read	Galy et al. (2012)
2	Time pressure	*Tp*	The pressure readers encounter while performing a demanding reading task	Galy et al. (2012); Choi et al. (2014)
3	Task presentation	*Tn*	The way the task is presented to the reader (e.g., textual or graphical)	Mayer and Moreno (2003)
4	Experience level	*El*	Prior experience towards a particular reading task	Choi et al., (2014)
5	Prior knowledge	*Pk*	Initial knowledge a reader has related to a particular reading task	Shen and Chu (2014)
6	Physical environment	*Pe*	The effects of the environment on readers (e.g. noise, brightness, and temperature)	Choi et al. (2014)
7	Reading Norm	*Rn*	The basic capability of reading (literacy) that someone possess to perform a related reading task	Elliott, Kurz, Beddow, and Frey (2009)
8	Personal Profile	*Pp*	Readers' personality	Rose et al. (2002)

These factors are representing a combination of three different dimensions which are individuals' (readers) characteristics, environment characteristics, and task-related dimensions. Apart from exogenous factors, instantaneous factors were also identified and summarized in Table 4.2.

Table 4.2

Instantaneous Factors

No.	Concept	Nomenclatures	Description	Reference
1	Situational aspects	*Sa*	Condition of the external situation such as time pressure, physical environment, and task presentation.	Bosse, Both, van Lambalgen, and Treur (2008)
2	Reading effort	*Rf*	The amount of effort a reader took to achieve the assigned reading task.	Hockey (1997)
3	Reading goal	*Rg*	Reader's willingness to stay focus when performing a reading task.	(Hockey, 1997; Bosse, Both, Van Lambalgen, & Treur, 2008)
4	Reading demand	*Rd*	The amount of difficulties reader has to encounter throughout the process.	(Kalyuga, 2011b; Sweller, 2011; Choi et al., 2014)
5	Motivation	*Mv*	A reader's desire or internal feeling to stay positive and solve the reading task.	Schnotz et al. (2009)
6	Expertise level	*Ev*	Knowledge and experiences for particular subjects.	(Nicholson & O'Hare, 2014; Shen & Chu, 2014)
8	Extraneous load	*Ed*	The external load caused by external variables of situational aspects.	(Oviatt, 2006; Sawicka, 2008; Paas & Sweller, 2012)
9	Intrinsic load	*Id*	Task complexity related load	(Oviatt, 2006; Sawicka, 2008; Paas & Sweller, 2012)
10	Germane load	*Gd*	The positive load that leads to the promising learning outcomes.	(Oviatt, 2006; Sawicka, 2008; Paas & Sweller, 2012)

Table 4.2 continued.

11	Germane resources	*Gr*	Reader's mental resources to handle intrinsic and extraneous load.	(Sweller et al., 2011)
12	Mental load	*Ml*	The total amount of experienced load	(Kalyuga, 2011b; Sweller, 2011; Choi et al., 2014)
13	Mental effort	*Me*	The amount of capacity or resources allocated to accommodate the task.	(Kalyuga, 2011b; Sweller, 2011; Choi et al., 2014)
14	Mental ability	*Ma*	Reader's mental ability to regulate the level of mental effort based on available resources.	(Kirschner, 2002; Sweller, 2011; Choi et al., 2014)
15	Experienced exhaustion	*Ex*	The short-term level of physical exhaustion experienced during reading process.	(Aziz, Ahmad, & Hintaya, 2012; Treur, 2011; Schaffner, Wagner, & Neckel, 2017)
16	Cognitive exhaustion	*Ce*	Cognitive or mental exhaustion as a result of an intricate reading task.	(Aziz, Ahmad, & Hintaya, 2012; Treur, 2011; Schaffner, Wagner, & Neckel, 2017)
17	Recovery effort	*Re*	Reader's ability to recover after sustained exposure to exhaustion resulted from the demanding task demands.	(Bosse, Both, Van Lambalgen, & Treur, 2008; Treur, 2011)
18	Short term exhaustion	*Sh*	Short-term exhaustion level as a result from the combination between mental and physical exhaustion	(Aziz, Ahmad, & Hintaya, 2012; Treur, 2011; Schaffner, Wagner, & Neckel, 2017)

Table 4.2 continued.

19	Critical point	*Cp*	The amount of individual effort that can be generated without becoming exhausted.	(Hockey, 1997; Bosse, Both, van Lambalgen, & Treur, 2008; Treur, 2011)
20	Reading engagement	*Rm*	The overall reader ability to stay focus during the reading process.	(Schnotz et al., 2009; Mills, Bosch, Graesser, & D'Mello, 2014)

The interaction between instantaneous and exogenous factors with respect of delayed contribution generates temporal factors. Table 4.3 summarizes the identified temporal factors of the developed cognitive agent model.

Table 4.3

Temporal Factors

No.	Factor	Nomenclatures	Description	Reference
1	Persistence	*Pr*	The prolonged existence of reading/problem solving efforts.	(Schnotz et al., 2009).
2	Cognitive load	*Cl*	The total amount of effort being used in the working memory while trying to achieve a reading task.	(Sweller et al., 2011).
3	Accumulative experienced exhaustion	*Ax*	The long-term exposure of physical exhaustion such as eye strain and back pain.	(Treur, 2011; Aziz, Ahmad, & Hintaya, 2012; Schaffner, Wagner, & Neckel, 2017).

Table 4.3 continued.

4	Accumulative exhaustion	*Ae*	The overall experienced mental and physical exhaustion	(Aziz, Ahmad, & Hintaya, 2012; Treur, 2011; Schaffner, Wagner, & Neckel, 2017)
5	Reading performance	*Rp*	Reader's performance in terms of stay focused and engaged while reading	(Kalyuga, 2011b; Sweller, 2011; Choi et al., 2014)

The interactions among all the identified relationships to build the intended model are presented in next section.

4.2 Conceptual Design

The whole essential and related cognitive load and reading performance factors from the previous section were used to construct the conceptual design of the computational cognitive agent model. Based on theoretical grounded relationships, these factors were constructed to regulate values ranging from 0 (low) to 1 (high). For the sake of brevity, the identified factors were composed into five different groups, namely; exogenous factors, exhaustion, load, persistence, and performance to construct a simplified conceptual design of the cognitive agent model (as depicted in Figure 4.1). These groups were labelled according to the external (model's inputs) and temporal factors.

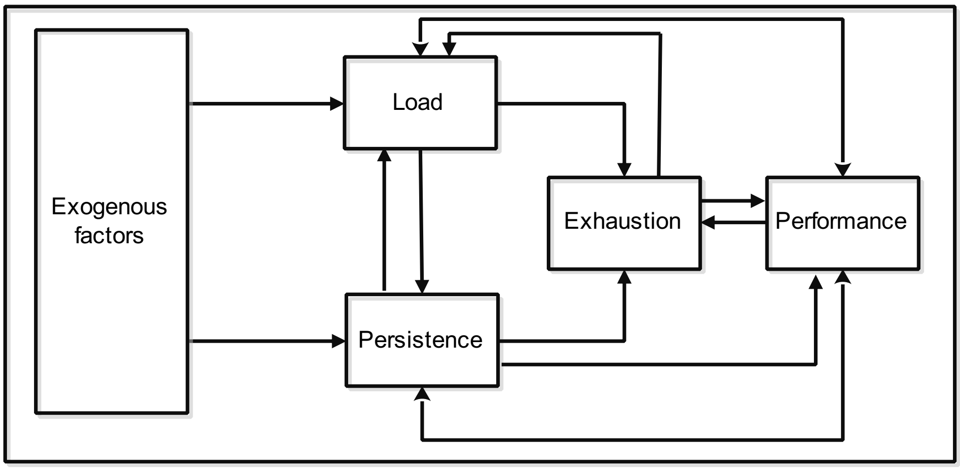

Figure 4.1. Components of a Cognitive Agent Model for Cognitive Load and Reading Performance

Figure 4.2 depicts the detailed interconnected nodes of the conceptual model. The interaction between these nodes determines the new (current) value of each node, either by a series of accumulations (temporality) or instantaneous (state) contributions.

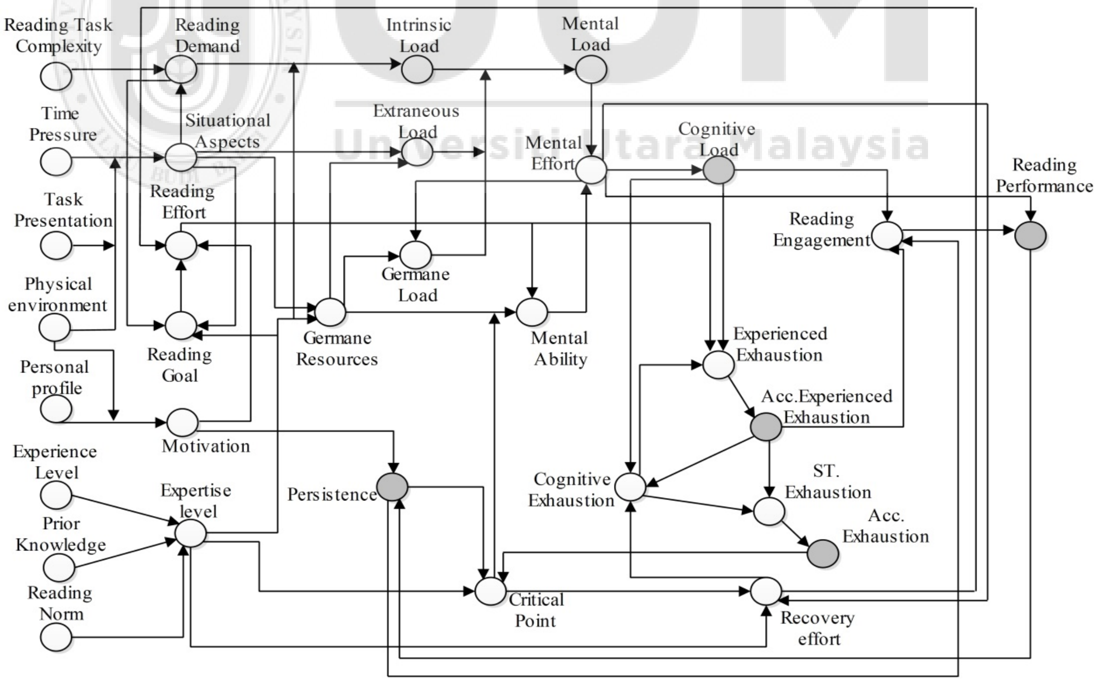

Figure 4.2. Global Relationships of Variables Involved in the Cognitive Load and Reading Performance

The dark grey nodes in Figure 4.2 represent the temporal relationships while all white nodes are the instantaneous relationships. The next section deals with the model formalization steps.

4.3 Operational Design

Basically, the outcome from this phase is an executable formal cognitive agent model of cognitive load and reading performance. This outcome provides a platform for simulation and explorations to take place in getting deeper insights on the correctness of the model. This conceptual design of cognitive load and reading performance (as presented in Figure 4.2) was formalized using First-Order Differential Equations based on the *Network Oriented Modelling* approach.

Towards this, several parameters were used to control and regulate the contributions of the model states. These parameters were introduced to simulate the causal relationships existed in the real-world as not all relationships are equally important. The degree of significant relationships between all underlying factors (e.g. equal weightage) can be presented by the notion of states and connection between them (Treur, 2017c). From this perspective, three different types of parameters were implemented to construct the causal relationships as detailed in Treur (2016c). These types are as follows:

- *Connection weights* were used to represent the strength of the connection.
- *Combination functions* were used to combine the causal impacts of more than a state on one state (e.g., sum function).
- *Speed factors* were used to represent how fast a state is changing upon causal impact.

In more details, the following sections described the formalization processes of the conceptual model that were discussed in Section 4.2.

4.3.1 Formalization of Load Components

Within the causal conceptual model as presented in Figure 4.2, the instantaneous factors were formalized to get insights on the temporal dynamics of cognitive load and reading performance development. The highlighted part of Figure 4.3 presents the causal relationships for load components.

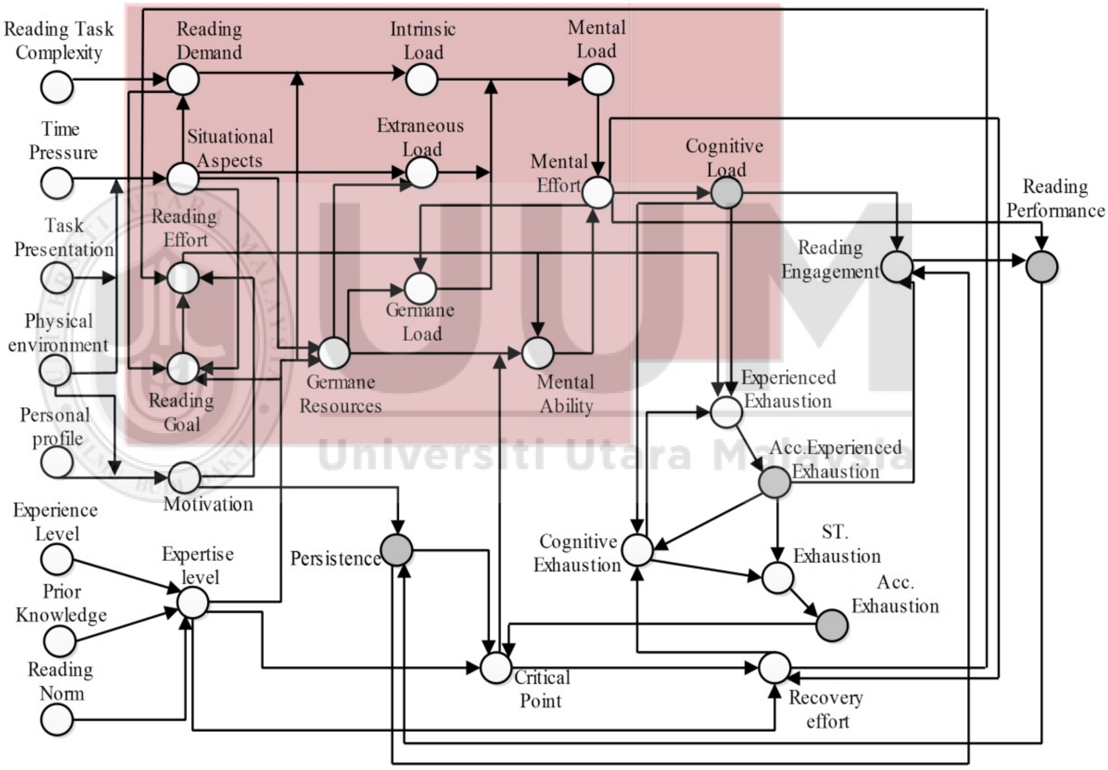

Figure 4.3. Causal Relationships for Load Components

Basically, in the context of serious reading (i.e., reading processes that lead to learning occurrence), a reader experiences a particular level of demands (reading demand (*Rd*)) which deem the results from reading task complexity (*Tc*) and the external effects of the environment (Kalyuga, 2011b; Sweller, 2011; Choi et al., 2014). It means the condition where reading materials are presented in improper ways, under time pressure and in an inappropriate condition (e.g., noisy environment). Both of reading task complexity (*Tc*) and situational aspects (*Sa*) correlate positively towards the level of reading demand (Bosse et al., 2008). Thus, the reading demand was computed as the summation process of two states (*Tc* and *Sa*) and η_{rd} parameter is introduced to regulate the proportional effects (as shown in Equation 4.1).

$$Rd(t) = \eta_{rd}.Tc(t) + (1- \eta_{rd}).Sa(t) \quad (4.1)$$

Similarly, the situational aspects concept (*Sa*) was formalized using the combination of weighted sum between time pressure (*Tp*), physical environment (*Pe*), and task presentation (*Tn*). Moreover, both weight parameters w_{sa1} and w_{sa2} were used to regulate the contribution of time pressure and physical environment while, λ_{sa} was used to balance the contribution preferences between the effect of both time pressure and physical environment.

$$Sa(t)= \lambda_{sa}.[w_{sa1}.Tp(t) + w_{sa2}.Pe(t)]+ (1- \lambda_{sa}).[Tp(t).Pe(t).(1-Tn(t))] \quad (4.2)$$

Next, the reading goal (*Rg*) (represents reader's willingness to stay focused) (Hockey, 1997; Bosse, Both, van Lambalgen, & Treur, 2008) was computed by combining the contribution of expertise levels (*Ev*) and reading demand (*Rd*). However, any distractions arise from the situational aspects (*Sa*) play a significant element to impede reader's concentration. Both of weighted sum parameters w_{rg1}, w_{rg2} and regulatory parameter ζ_{rg} were used to control the contribution preferences in the equation.

$$Rg(t)= \zeta_{rg}.Ev(t) +(1- \zeta_{rg}).[w_{rg1}.Rd(t)+ w_{rg2}.(1-(Sa(t).(1-Ev(t))))] \quad (4.3)$$

where, $\sum_{i=1}^{2} w_{rgi} = 1$

Similar to Equation 4.3, reading effort (*Rf*) (Hockey, 1997) was represented as the sum value between motivation (*Mv*) levels and a reading goal. In addition, some fraction contribution of recovery effort (*Re*) contributes positively towards the reading effort. The weighted sum parameters w_{rf1}, w_{rf2} and regulatory parameter γ_{rf} were used to balance the contribution preferences

$$Rf(t) = \gamma_{rf}.(w_{rf1}.Mv(t) + w_{rf2}.Rg(t)) + (1-\gamma_{rf}).Re(t) \tag{4.4}$$

where, $\sum_{i=1}^{2} w_{rfi} = 1$

Germane resources level (*Gr*) was measured as the positive contribution of expertise level (*Ev*). It relates to the reader's available resources to accommodate the task and it determines by expertise level (Sweller et al., 2011). However, germane resources reacted negatively to the ω_{gr} proportional contribution of situational aspects (*Sa*).

$$Gr(t) = \omega_{gr}.Ev(t) + (1-\omega_{gr}).Ev(t).(1-Sa(t))) \tag{4.5}$$

Likewise, intrinsic load (*Id*) was calculated as the direct contribution of reading task demands (*Rd*) that imposed during reading and it is negatively correlated to the expertise level (*Ev*). It means the readers with accomplished skills (i.e., expertise level (*Ev*) is high) usually encounter very low cognitive demands during reading process (Oviatt, 2006; Sawicka, 2008; Paas & Sweller, 2012).

$$Id(t) = Rd(t).[(1-Ev(t))] \tag{4.6}$$

Later, the extraneous load (*Ed*) is computed as the effects from the interaction between available resources (Germane resources (*Gr*)) and situational aspects (*Sa*). The regulation parameter β_{ed} is used to determine the preferred proportional contributions for both situational aspects and germane resources. Germane resources provide a reverse effect to the formation of an extraneous load.

$$Ed(t) = \beta_{ed}.Sa(t) + (1-\beta_{ed}).Sa(t).(1-Gr(t)) \tag{4.7}$$

In the case of germane load (*Gd*), this specification is analysed based on the proportional contribution of mental effort (*Me*) and germane resources (*Gr*). It has a similar computational structure of extraneous load. Towards this end, germane load is positively correlated to the mental effort (Oviatt, 2006; Sawicka, 2008; Paas & Sweller, 2012). Similar to the extraneous load, germane resources also reduce the overall effect of germane load. Besides, γ_{Gd} parameter was used to regulate the proportional contribution of the overall germane load effects.

$$Gd(t) = \gamma_{gd}.Me(t) + (1-\gamma_{gd}).Me(t).(1-Gr(t)) \tag{4.8}$$

Mental load (*Ml*) can be represented as the positive weighted sum of intrinsic load (*Id*), extraneous load (*Ed*), and germane load (*Gd*). The combination of these three loads determines the overall level of mental load.

$$Ml(t) = w_{ml1}.Id(t) + w_{ml2}.\mathrm{Ed}(t) + w_{ml3}.Gd(t) \tag{4.9}$$

Where, $\sum_{i=1}^{3} w_{mli} = 1$

Identical to Equation 4.9, reader's mental ability (*Ma*) is determined by the combination of germane resources (*Gr*), reading effort (*Rf*), and critical point (*Cp*). These three factors are essential to determine mental ability that enables readers to make use of their available resources to tackle the given task demands (Kalyuga, 2011b; Sweller, 2011; Choi et al., 2014). Parameters w_{ma1}, w_{ma2}, and w_{ma3} were used to control the positive contribution of each factor.

$$Ma(t) = w_{ma1}.Rf(t) + w_{ma2}.Cp(t) + w_{ma3}.Gr(t) \quad (4.10)$$

where, $\sum_{i=1}^{3} w_{mai} = 1$

In addition, the reader's mental ability is a significant element in maintaining the level of mental effort (*Me*). It also crucial as a basis to perform a reading task and accommodate any associated load.

$$Me(t) = (1 - Ma(t)).Ml(t) \quad (4.11)$$

From Equation 4.11, mental effort is determined by multiplying the effects of mental load (*Ml*) with the experienced mental ability. The high mental ability level reduces mental effort. This scenario explains why expert individuals (with high mental ability) need lesser effort to perform different task compared to the novice. Finally, the continuous exposure towards mental effort in a time interval between t and $t + \Delta t$ results the accumulation of cognitive load (*Cl*) (Sweller et al., 2011). The speed parameter β_{Cl} is used to determine the change rate of a cognitive load level over time.

$$Cl(t+\Delta t) = Cl(t) + \beta_{Cl}.(Me(t) - Cl(t)).Cl(t).(1 - Cl(t)).\Delta t \quad (4.12)$$

Note that the equation *Cl*(*t*).(1-*Cl*(*t*) part regulates the limit of temporal boundary values (either *Cl* → 1 or *Cl* → 0).

4.3.2 Formalization of Persistence Components

In this model, other instantaneous factors that can be categorized under the persistence components are highlighted in Figure 4.4. The formalization of these factors is explained as follows.

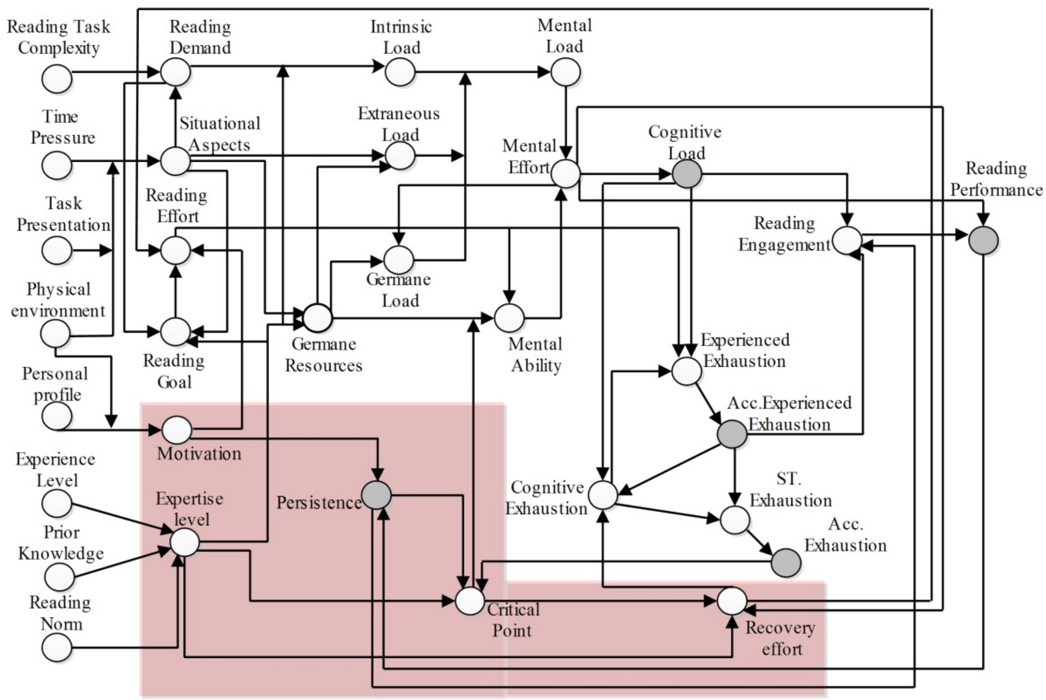

Figure 4.4. Causal Relationships under Persistence Components

Expertise level (*Ev*) is defined as an *acquired knowledge in subject matters* (Nicholson & O'Hare, 2014; Shen & Chu, 2014). Therefore, it can be represented using the weighted sum of an experience level (*El*) and prior knowledge (*Pk*). Furthermore, the proportional contribution of reading norm (*Rn*) (i.e., the basic ability to read the given materials) also contributes positively towards the expertise level and regulated via ζ_{ev} proportional contribution parameter.

$$Ev(t) = \zeta_{ev}.(w_{ev1}.El(t) + w_{ev2}.Pk(t)) + (1 - \zeta_{ev}).Rn(t) \quad (4.13)$$

Recovery effort (*Re*) is determined by the positive differences between the weighted sum of critical point (*Cp*), expertise level (*El*), and mental effort (*Me*). In this case, if the mental effort approaches its boundary point, then a reader experiences difficulty to perform the task (Bosse, Both, van Lambalgen, & Treur, 2008; Treur, 2011).

$$Re(t) = Pos((w_{re1}.Cp(t) + w_{re2}.Ev(t)) - Me(t)) \quad (4.14)$$

It is worth mentioning that w_{re1} and w_{re2} were used to regulate the contribution of critical point and expertise level while *Pos* operator is defined as follows:

$$Pos(x) = (x + |x|)/2, \text{ or alternatively; } Pos(x) = x \text{ if } x \geq 0 \text{ and } 0 \text{ else.}$$

where, $\sum_{i=1}^{2} w_{rei} = 1$

Moreover, the ability of a reader to generate additional effort (critical point (*Cp)*) without becoming exhausted (Hockey, 1997; Bosse, Both, Van Lambalgen, & Treur, 2008; Treur, 2011) is measured from the direct effect of expertise level (*El*) and the proportional contribution of persistence (*Pr*). However, when a reader becomes exhausted (*Ae*), the critical point decreases proportionally to the experienced exhaustion.

This concept was formalized to compute critical point as shown in Equation 4.15. In this equation, α_{cp} parameter is used to regulate the contribution those three aforementioned factors.

$$Cp(t)= \alpha_{cp}.Ev(t)+(1- \alpha_{cp}).Pr(t).Ev(t) .(1-Ae(t)) \quad (4.15)$$

Pertinent to motivation (*Mv*), it depends on the reader's positive personality (*Pp*) (for instance: *openness* versus *neuroticism*) and the disturbance level from physical environment (*Pe*). In other words, a reader will be motivated in a comfortable (ambience) environment or when s(he) possess positive personality (i.e., low in neuroticism) (Schnotz et al., 2009, Daitkar, 2017). The regulatory parameter λ_{mv} is used to control the overall contribution between personal profile and physical environment.

$$Mv(t)= \lambda_{mv}. Pp(t)+(1-\lambda_{mv}).(1-Pe(t)) \quad (4.16)$$

The persistence level is measured as a constant high level of the weighted sum between motivation and reading performance (*Rp*). It should be noted that the change process is measured in a time interval between *t* and *t*+Δ*t*. The ω_{Pr} is used as a change rate parameter while β_{dp} represents the decay in persistence throughout the time.

$$Pr(t+\Delta t) = Pr(t) + \omega_{Pr}.[[w_{pr1}.Mv(t) + w_{pr2}.Rp(t)] - Pr(t) - \beta_{dp}].(1-Pr(t)).Pr(t).\Delta t \quad (4.17)$$

where, $\sum_{i=1}^{2} w_{pri} = 1$

4.3.3 Formalizations of Exhaustion Components

There are several instantaneous and temporal factors were grouped under the exhaustion components. Figure 4.5 depicts the underlying factors under exhaustion components and their formalized forms are presented as the followings:

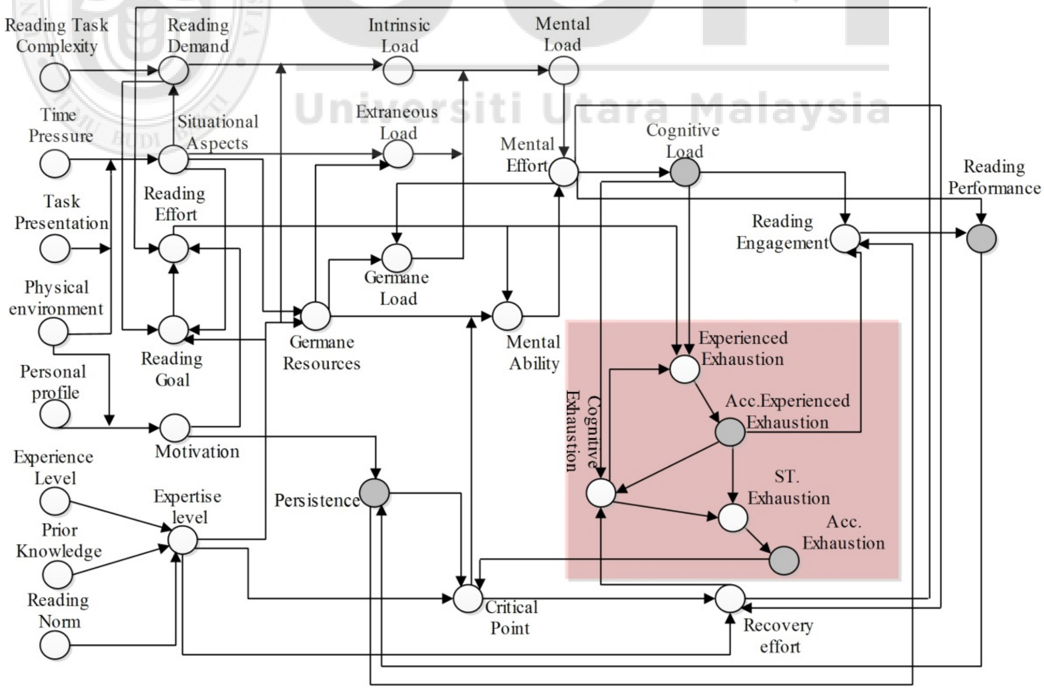

Figure 4.5. Causal Relationships for Exhaustion Components

Throughout time, the reader will experience a certain level of exhaustion that later decreases performance (experienced exhaustion (*Ex)*). This reflects the level of tiredness as the combination impacts of cognitive load (*Cl*) and cognitive exhaustion (*Ce*) (i.e., mental exhaustion). This impact of experienced exhaustion could be mitigated if a reader put more reading effort (*Rf*) to accomplish the task (Bosse, Both, van Lambalgen, & Treur, 2008; Treur, 2011). Therefore, the experienced exhaustion can be represented by using weighted sum of cognitive load, cognitive exhaustion, and the amount of reading effort.

$$Ex(t) = (w_{ex1}.Cl(t) + w_{ex2}.Ce(t)).(1-Rf(t)) \tag{4.18}$$

where, $\sum_{i=1}^{2} w_{exi} = 1$

As time progresses, constant exposure towards an experienced exhaustion event (*Ex*) generates an accumulative effect of experienced exhaustion (*Ax*). The accumulation effect occurs in a time interval between t and $t+\Delta t$.

$$Ax(t+\Delta t) = Ax(t) + \eta_{Ax}.Ex(t).(1-Ax(t)).\Delta t \tag{4.19}$$

Moreover, the Equation 4.19 depicted that an accumulative experienced exhaustion level will always increase steadily due to normal physical tiredness experienced throughout time. In this case, there is no possibility it can be reduced unless a proper break is taken. Also, the change rate η_{Ax} is used as well to regulate the speed change in the accumulative experienced specification.

On the other hand, cognitive exhaustion (mental exhaustion (*Ce*)) is measured as a proportional contribution α_{ce} of cognitive load (*Cl*) and accumulative experienced exhaustion (*Ax*). The overall mental exhaustion is controlled at the minimum level by the existence of recovery effort (*Re*).

$$Ce(t) = (\alpha_{ce}.Cl(t) + (1-\alpha_{ce}).Ax(t)).(1-Re(t)) \tag{4.20}$$

Finally, for both physical and mental exhaustion levels, these factors contributed to generate an overall effect of a long-term exhaustion level (*Ae*) (Aziz, Ahmad, & Hintaya, 2012; Treur, 2011; Schaffner, Wagner, & Neckel, 2017). The cognitive exhaustion (*Ce*) and accumulative experienced exhaustion (*Ax*) are effected from the constant build-up of a short term exhaustion level (*Sh*) over time. The constant exposure towards a short-term exhaustion condition causes a direct impact to generate an overall or temporal exhaustion (*Ae*).

$$Sh(t)=\mu_{st}.Ce(t)+(1-\mu_{st}).Ax(t) \tag{4.21}$$

$$Ae(t+\Delta t)=Ae(t)+\beta_{Ae}.(Sh(t)-Ae(t)).Ae(t).(1-Ae(t)).\Delta t \tag{4.22}$$

It is important to specify that μ_{st} parameter is used to balance the equation. Similarly, β_{Ae} is used to control the change rate of an accumulative experienced exhaustion over time.

4.3.4 Formalization of Performance Components

This section presents the formalization process and interplays of performance components (as in Figure 4.6). The last two temporal-dynamic factors to be formalized in the model are reading engagement (*Rm*) and reading performance (*Rp*). In reading engagement, this factor is determined from the positive contribution of persistence (*Pr*) (Schnotz et al., 2009; Mills, Bosch, Graesser, & D'Mello, 2014). This concept is related to the readers who stick at a high engagement level to perform a reading task. However, the reading engagement will be disengaged after readers experienced a high constant cognitive load (*Cl*) level or an overwhelming accumulative experienced exhaustion (*Ax*) (Sweller et al., 2011). To this end, Equation 4.23 was made to formalize the reading engagement concept. In the same way as in Equation 4.18, the weighted sum parameters w_{rm1} and w_{rm2} were used to regulate the underlying contribution from both factors.

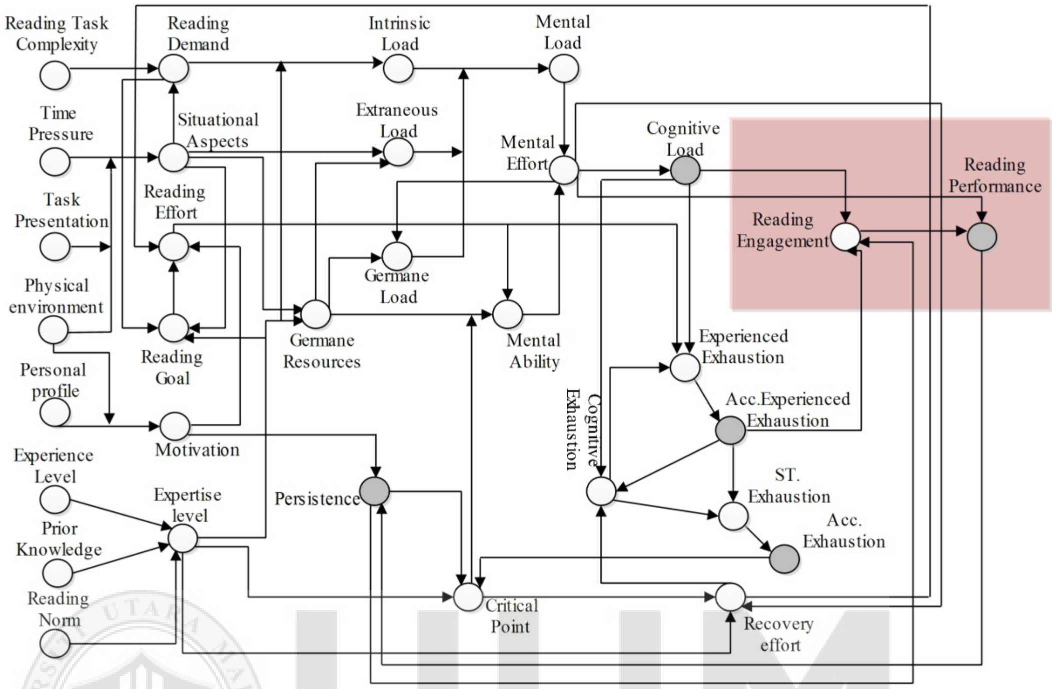

Figure 4.6. Causal Relationships under Performance Components

$$Rm(t)=Pr(t).[1-(w_{rm1}.Ax(t)+w_{rm2}.Cl(t))] \quad (4.23)$$

where, $\sum_{i=1}^{2} w_{rmi} = 1$

Generally, the reading engagement correlates positively with the reading performance (*Rp*) (Boaler, Dieckmann, Perez Núñez, Liu Sun, & Williams, 2018; Groccia, 2018). However, the overall reading performance is hampered by the formation of mental effort (Choi et al., 2014). The large consuming amount of mental effort level indicates that a demanding reading task will disturb reading process at later time point.

$$Rp(t+\Delta t)=Rp(t)+\eta_{Rp}.[((1-Me(t)).Rm(t))-Rp(t)].(1-Rp(t)).Rp(t).\Delta t \quad (4.24)$$

The reading performance is formalized in a time interval between t and $t+\Delta t$ with a speed change factor η_{Rp}.

4.4 Simulation Results for Cognitive Agent Model

Upon the completion of conceptual and operational design of the cognitive agent model, a simulator was developed to reproduce the properties of instantaneous and temporal relationships based on the real-world behaviours. Due to its computational efficiency, a numerical programming platform Matlab, has been used tremendously in the previous research works to mimic agents' behaviours for simulation experiments (Abro et al., 2014; Bosse et al., 2015; Adegoke, Aziz, & Yusof, 2015; McCarthy & Achenie, 2017). To understand the implementation of the model in Matlab simulation environment, the execution process is presented in Algorithm 4.1.

Algorithm 4.1: Domain Model Implementation

1. **Input**: number of fictional agents
2. **Output**: simulation traces
3. **Start**
4.   **Initialization**
5.   *n*← number of fictional agents
6.   Initialize numStep =maxNumStep
7.   Initialize parameters values
8.   Initialize temporal factors values
9.   **For** i←1 to *n* **do**
10.   **For** *j*← *i* to numStep **do**
11.   exogenous_var (*i*, *j*) ← initial values
12.   **For** *x*←1 to *n* **do** // at time 1
13.   instantaneous_var (*x*, *1*) ← instantaneous equations
14.   **For** *i*←1 to *n* **do**
10.   **For** *j*← *i* to numStep **do** // at time 2
11.   instantaneous_var (*i*, *j*) ← instantaneous equations
12.   temporal_var (*i*, *j*) ← temporal equations
13.   **Plot** required graphs
14. **End**

Algorithm 4.1 explains the general steps in implementing a cognitive agent model for a number of fictional *n* agents. First, all parameters, temporal factors, and time steps (*numStep*) (i.e., the allocated time to perform a reading task) are initialized to specific initial values. Then, the exogenous factors of each fictional agent are also initialized to obtain a set of simulation traces for different scenarios. After the initialization process, all instantaneous equations for the fictional agents at time one (*numStep*=1) were computed. In addition to this, the simulation cycle begins at the initialized number of steps equal to two (numStep =2). The obtained simulated values of the instantaneous and temporal factors can be used to generate traces.

In this study, three different scenarios pertinent to three fictional (individuals) were chosen. These scenarios are as the following; Agent ***A***: demanding task, and the reader is expertise and less motivated, Agent ***B***: demanding task, and the reader is expert and highly motivated, and Agent ***C*:** demanding task, and the reader is not expert and less motivated. For this experiment, different initial settings are used to generate simulation traces. These initial settings are summarized in Table 4.4.

Table 4.4

Initial Settings for Exogenous Factors

Exogenous factors	**Formalization**	**Initial settings**		
		Agent A	**Agent B**	**Agent C**
Reading task complexity	*Tc*	0.9	0.9	0.9
Time pressure	*Tp*	0.9	0.9	0.9
Personal profile	*Pp*	0.1	0.9	0.1
Task presentation	*Tn*	0.1	0.1	0.1
Physical environment	*Pe*	0.9	0.1	0.9
Prior knowledge	*Pk*	0.9	0.9	0.1
Experience level	*El*	0.9	0.9	0.1
Reading norm	*Rn*	0.9	0.9	0.8

These settings represent the initial conditions, a reader has experienced prior to perform a reading task, ranging from 0 (lowest impact) to 1 (highest impact). For example, the reading task complexity is initialized as 0.9 (for all cases) to represent an extremely difficult task that can only be solved by accomplished readers. Furthermore, for an agent ***C***, both prior knowledge and experience levels were initialized as 0.1 to represent poor skills in performing the reading task. Moreover, from the conducted experiments, any value equal or greater than 0.5 is considered as "high". In the same vein, temporal relationships are also assigned to the initial values as in Table 4.5. These initial values were chosen based on a set of systematic analysis conducted to evaluate possible variations of initial temporal values to clearly understand the model response to changes in the temporal values.

Table 4.5

Initial Settings of the temporal factors

Temporal factors	**Formalization**	**Agent A**	**Agent B**	**Agent C**
		Initial settings		
Accumulative exhaustion	*Ae*	0.3	0.3	0.3
Reading performance	*Rp*	0.3	0.3	0.3
Persistence	*Pr*	0.3	0.3	0.3
Accumulative experienced exhaustion	*Ax*	0	0	0
Cognitive Load	*Cl*	0.1	0.1	0.1

For example, for an agent ***B****,* different values ranged between 0 and 1 are used as initial values for accumulative exhaustion (*Ae*) and persistence (*Pr*) with time-steps of 1000. Pertinent to the persistence level, after a number of simulation runs (from the various initialized values), it can be clearly concluded that the final experimental results yielded to a similar convergence value (as depicted in Figure 4.7).

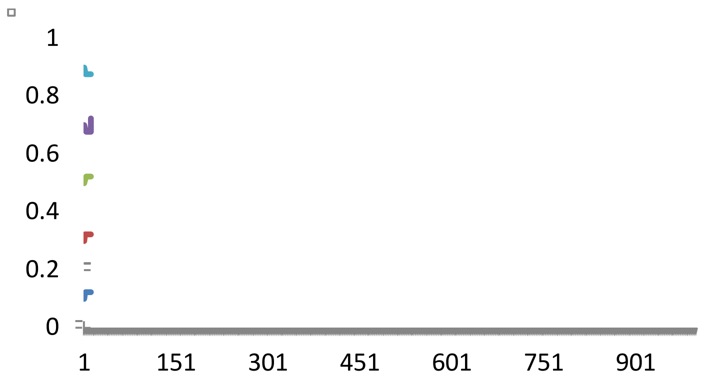

Figure 4.7. Convergence Point for Different Initial Variations in Persistence

Likewise, despite of different initialized values for an accumulative exhaustion (*Ae*) level (at numStep = 1), the final simulation outcomes are converged at the same stability point (as depicted in Figure 4.8).

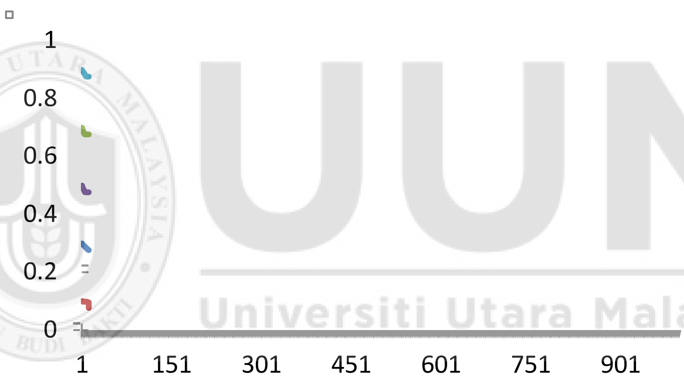

Figure 4.8. The Convergence Point for Different Initial Values in Accumulative Exhaustion

In this study, the initial temporal value for the accumulative experienced exhaustion is initialized as zero. The purpose behind this is to explain that the tiredness level is normally low prior to perform any particular tasks. In addition, specific initial values are assigned for each model's parameters to represent personalized characteristics for each reader. Note here, the default setting for all parameters is 0.5 (or 50 percent contribution for each parameter), unless being specified as in Table 4.6.

Table 4.6

Initial Settings of Model's Parameters

Parameters	Initial value	Description
numStep	500	Representation of reading task up to four hours
Δt	0.5	Representation of a change in time steps
λ_{sa}	0.1	Proportional parameter for situational aspects
w_{ml2}	0.4	Weight parameters for the mental load
w_{ml3}	0.1	
w_{ma1}, w_{ma2}, w_{ma3}	0.3	Weight parameters for the mental ability
w_{re1}	0.9	Weight parameters for the recovery effort
w_{re2}	0.1	
β_{Ae}	0.08	Speed factor for an accumulative exhaustion level
β_{Cl}	0.3	Speed factor for a cognitive load level
ω_{Pr}	0.9	Speed factor for a persistence level
β_{dp}	0.01	Decay parameter for a persistence level
η_{Ax}	0.03	Speed factor for an accumulative experienced exhaustion level
β_{ed}	0.9	Proportional parameter for an extraneous load

The aforementioned parameters values were obtained as the results from conducted systematic experiments to explore the model's reaction towards changes in exogenous factors. These experiments are very essential to observe possible degree to which changes in parameters values has impacted the overall simulation results. For this particular point, the agent ***B*** is executed where only one parameter is changed at each time while preserving the other parameters. For example, the contribution factor for temporal parameter ω_{Pr}, (parameter for persistence level), is varied between 0.1 and 0.9 with maximum time steps equal to 1000 (Δt =0.3). The obtained results from this experiment are visualized in Figure 4.9.

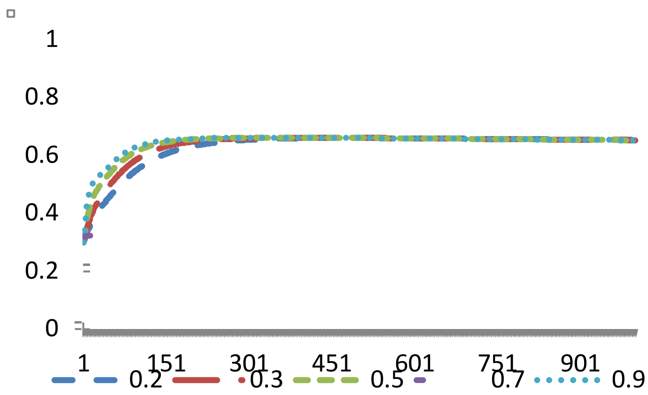

Figure 4.9. Effects of Variation in ω_{Pr}

These experimental results have demonstrated that variations in parameter ω_{Pr} give a similar impact to the final persistence level. However, some minor changes (either by increasing or decreasing the values) were observed in the beginning of the simulation. This is a very interesting finding as it shows that changes within the temporal parameter value are capable to present a set of possible variations for different individuals. Another example is the effect of a proportional parameter μ_{st}, in short-term exhaustion (*Sh*). This specification is derived from both cognitive exhaustion (*Ce*) and accumulative experienced exhaustion (*Ax*):

$$Sh(t) = \mu_{st}.Ce(t) + (1-\mu_{st}).Ax(t)$$

For the parameter analysis, its value has a number of variations ranging from 0.1 to 0.5 (by intervals of 100) denoted with time-steps of 500 (Δt =0.3). Therefore, by increasing the level of μ_{st}, the short-term exhaustion level decreases gradually (as depicted in Figure 4.10).

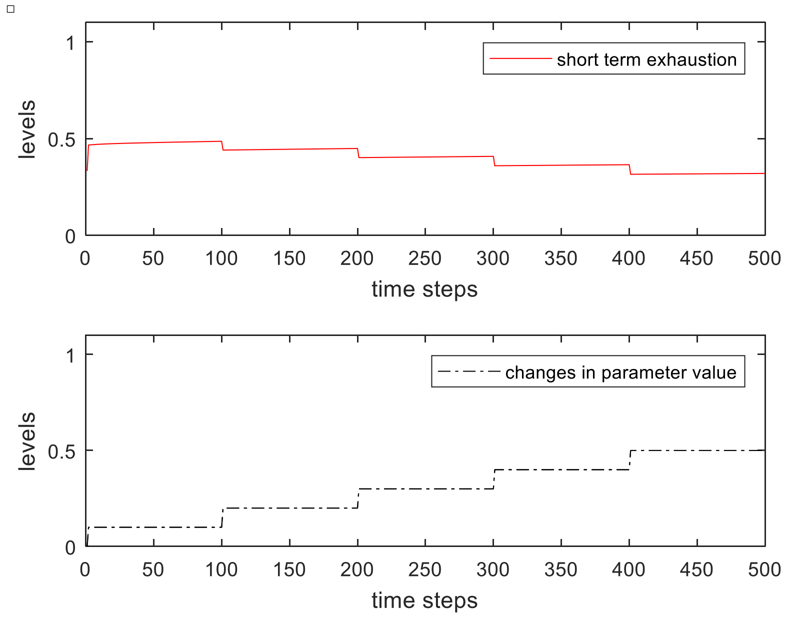

Figure 4.10. Effects of Variation in μ_{st}

This is due to the increment in μ_{st} value that reduces the contribution of an accumulative experienced exhaustion (i.e., tiredness level). However, the tiredness level is constantly increasing when performing any particular task. Besides, when μ_{st} is equal to one, there is no clear difference of the simulated results. Thus, with regard to the previous initialized parameter settings for three aforementioned fictional readers, the next sections explain the simulation results from these experimental designs.

4.4.1 Cognitive Load

In this section, the simulation results of cognitive load for all three aforementioned fictional characters will be described. In the case of agent ***A***, this agent represents a condition when a reader is performing a demanding reading task that requires a high mental effort to be accomplished. However, despite the complexity of the task (e.g., solving mathematics or physics assignments) a reader with accomplished skills is capable to cope with these demands (Nicholson & O'Hare, 2014; Shen & Chu, 2014).

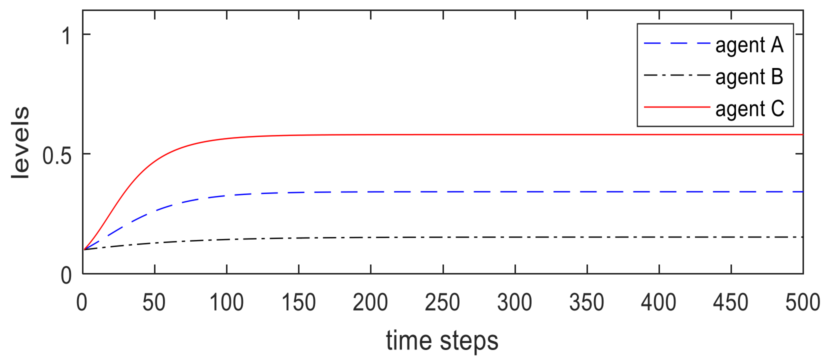

Figure 4.11. Simulation Results of Cognitive Load

Hence, this explains his/her low cognitive load level as depicted in Figure 4.11. Note here, due to the low level of motivation (i.e., a highly neurotic personality reader, and situated within a non-conducive environment) the level of cognitive load is slightly high (Schnotz et al., 2009). This slight increment in cognitive load level is resulted from the high level of extraneous load as shown in Figure 4.12 (c). However, by improving reader's motivational level, it also reduces the risk of having a high cognitive load level (Schnotz et al., 2009). Similar scenario for low cognitive load cases also can be seen in agent ***B***. For this particular case, the agent is able to endure the imposed load as it can be observed in any highly skilled readers (i.e., high experience level, high prior knowledge, and reading norm is high), and a highly motivated reader (agent ***B*** has positive personality; i.e., openness) and a conducive environment to perform a reading task. In contrast to agent ***A*** and ***B***, agent ***C*** is exposed to the high level of cognitive load due to highly intense experienced demands (e.g., the task is too difficult, not well prepared, non-conducive environment, and limited allocated time to solve the task). Moreover, agent ***C*** is not motivated and has inadequate knowledge and experiences to solve the task. In this case, the high cognitive load was resulted due to the formation of high levels in intrinsic, extraneous, and germane loads (Sweller et al., 2011). The simulation results of these interrelated loads (intrinsic, extraneous, and germane load) are depicted in Figure 4.12.

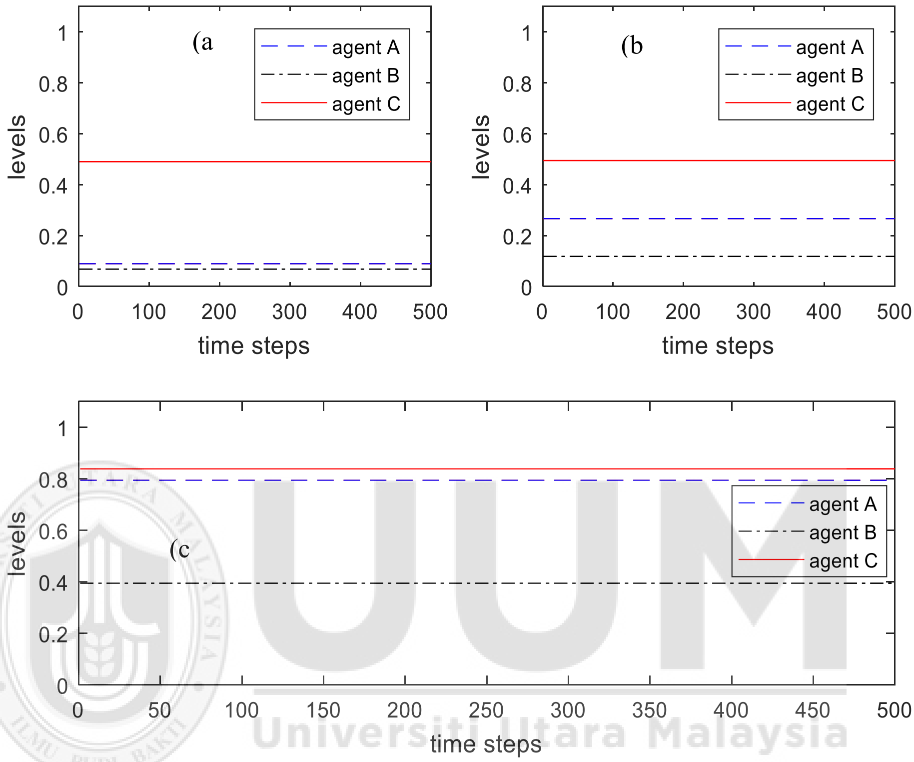

Figure 4.12. Simulation Results of (a) Intrinsic Load, (b) Germane Load, and (c) Extraneous Load

In addition, Figure 4.12 shows that readers with accomplished skills can endure the imposed intrinsic load as shown in the case of agents ***A*** and ***B***. In contrast, an agent ***C*** experiences a high level of intrinsic load due to the task difficulty and low motivation, and low levels in prior knowledge and experience (Oviatt, 2006; Sawicka, 2008; Paas & Sweller, 2012). In the same manner, this condition can be observed in a germane load level. Unlike agent ***B***, it can be clearly seen that an extraneous load level is high for both agent ***A*** and ***C*** as the combined results of non-conducive environment effects and task difficulties.

4.4.2 Accumulative Exhaustion

The formation of an accumulative exhaustion (*Ae*) for the aforementioned fictional agents is covered in this section. It can be seen that both agent ***A*** and agent ***B*** are expert readers (i.e., having accomplished skills in performing a reading task) and capable to easily accommodate assigned tasks (i.e., low cognitive load). However, both agents encounter a gradual increment in the level of accumulative exhaustion due to the natural physical tiredness (*Ax*) (e.g., eye strain and back pain) as a result for performing a task in a non-stop manner (as in Figure 4.14(c)) (Treur, 2011). The gradual increment effect in an accumulative exhaustion level (for agent ***A*** and ***B***) is visualized in Figure 4.13.

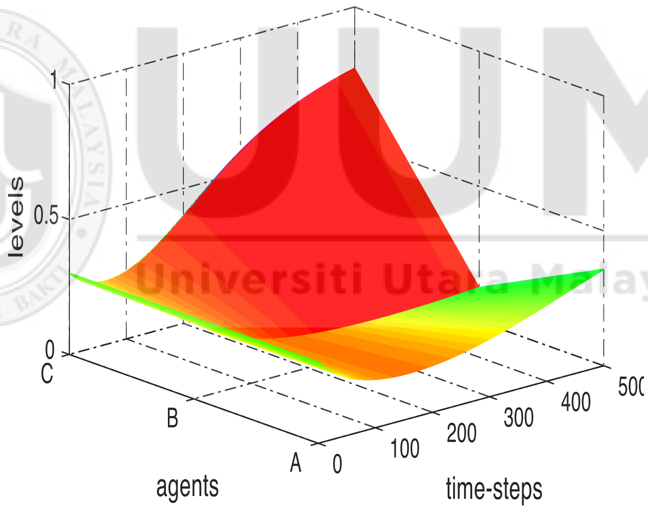

Figure 4.13. Simulation Results for an Accumulative Exhaustion Level

In contrast to agent ***A*** and ***B***, agent ***C*** is exposed to the high level of accumulative exhaustion (as shown in the Figure 4.13). The formation of a high accumulative exhaustion level is due to the agent having inadequate knowledge and experience to cope with the imposed load. Hence, it will encounter a high level of cognitive exhaustion (*Ce*) as depicted in Figure 4.14 (a). For this condition, the task difficulty, non-conducive environment, and inadequate knowledge and experience play a major role in creating a high level of cognitive exhaustion (Schaffner, Wagner, Neckel, 2017). As a result, the prolong exposure to cognitive exhaustion causes a high level of accumulative exhaustion in the long term (Cao, Wan, Wong, da Cruz, & Hu, 2014; Xie et al., 2016). Furthermore, low recovery from the exhaustive tasks also contributes to the development of accumulative exhaustion (Bosse, Both, van Lambalgen, & Treur, 2008; Treur, 2011). It means the recovery effort (*Re*) has been fully consumed and it is difficult for any individual to recover some efforts within limited time intervals. The simulation result of a recovery effort impact on an accumulative exhaustion level is shown in Figure 4.14(b).

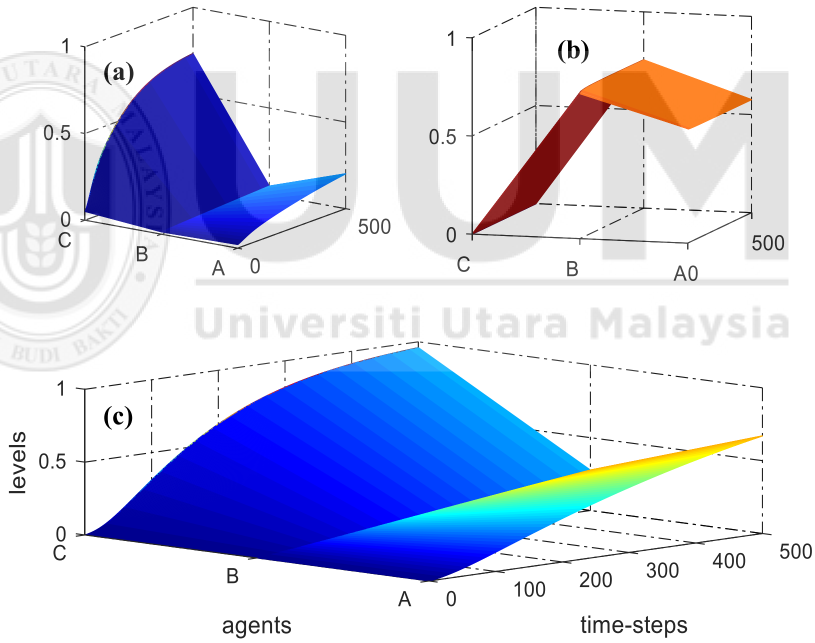

Figure 4.14. Simulation Results of a) Cognitive Exhaustion, b) Recovery Effort, and c) Accumulative Experienced Exhaustion

Based on the experimental settings for all fictional readers, the simulation results for all main factors (i.e., recovery effort, cognitive exhaustion, and accumulative experienced exhaustion) and their impacts towards the level of accumulative exhaustion are shown in Figure 4.14.

4.4.3 Accumulative Experienced Exhaustion

This section describes the simulation results pertinent to an accumulative experienced exhaustion level (*Ax*). It refers to the level of physical tiredness an individual encounters while performing any particular task (Treur, 2011; Aziz, Ahmad, & Hintaya, 2012; Schaffner, Wagner, & Neckel, 2017). Normally, a prolonged period of demanding cognitive activity results a high level of physical tiredness. In this study, the simulation result of an accumulative experienced exhaustion is presented in Figure 4.15. The results show that both agents ***A*** and ***C*** have experienced accumulated exhaustion at accelerated rate compared to an agent ***B***.

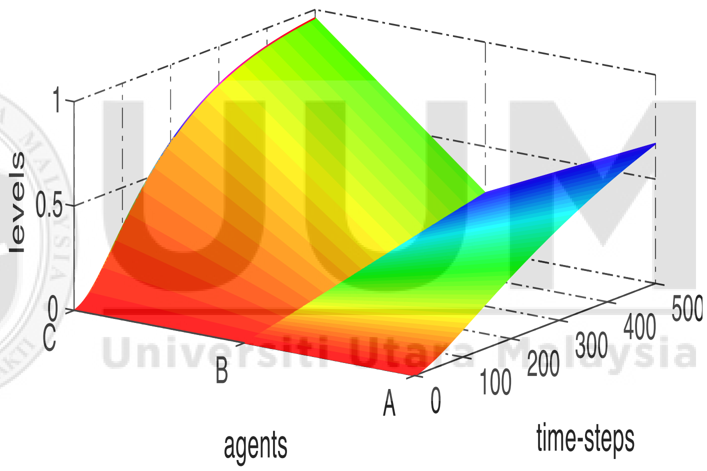

Figure 4.15. Simulation Result of Accumulative Experienced Exhaustion

This is due to the higher exposure towards cognitive load and exhaustion. Despite the agent ***B*** is resilient towards cognitive load and cognitive exhaustion, after a prolonged exposure term, the accumulative experienced exhaustion is slightly increased by its time-factor because of the physical tiredness. Furthermore, this condition has been observed in many related long-term duration events such as driving a car and manoeuvring an aircraft (Boksem & Tops, 2008; Marcora, Staiano, & Manning, 2009).

4.4.4 Persistence and Reading Performance

The simulation results of persistence (*Pr*) and reading performance (*Rp*) are depicted as Figure 4.16(a) and Figure 4.16(b) respectively. Pertaining to a persistence level, the simulation results visualized that both agents ***A*** and ***C*** are experiencing almost similar low-persistence level. The non-conducive environment and negative personality (i.e., they are not motivated) factors are among reasons for these identical results. Moreover, these simulation results are in line with the literature as in (Schnotz et al., 2009, Daitkar, 2017).

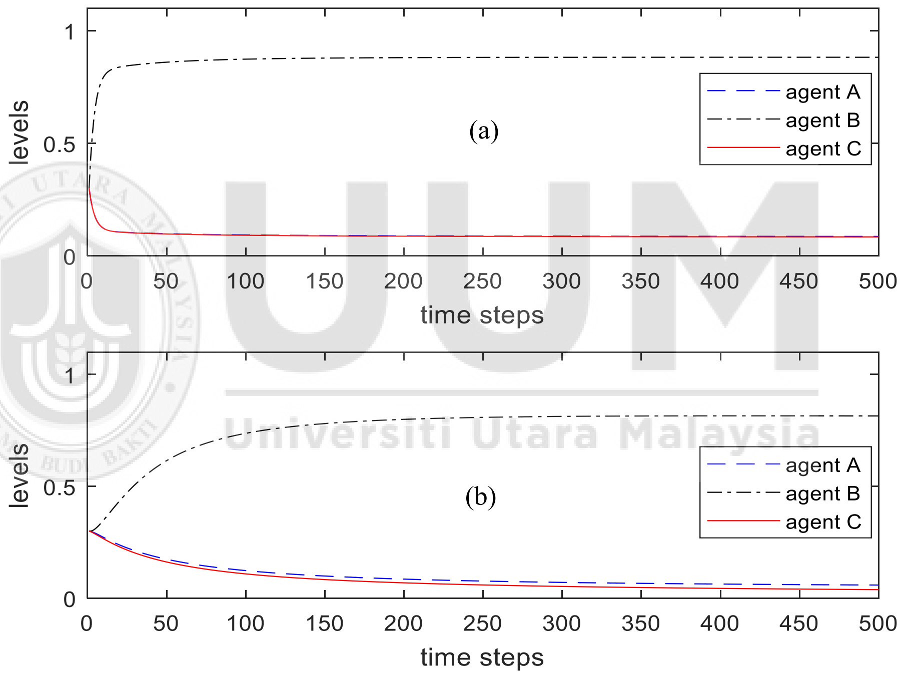

Figure 4.16. Simulation Results of a) Persistence and b) Reading Performance

Contrarily, an agent ***B*** has been able to regulate the overall motivational level that later leads to the consistent improvement in the overall persistence level as in Figure 4.17. Both agents ***A*** and ***C*** are experiencing almost similar low-motivation level. This condition is visualized in Figure 4.17.

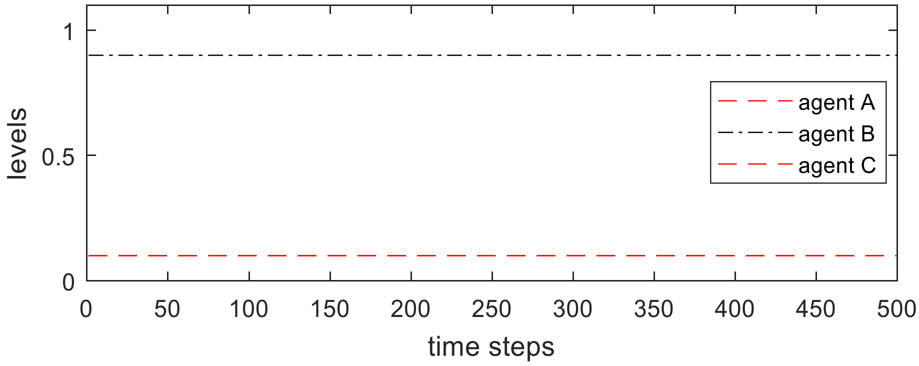

Figure 4.17. Simulation Results for Motivation

When it comes to the reading performance level, it represents to which extent a reader is performing a meaningful and seamless reading process. As a result, the level of reading performance is decreasing when the cognitive load and exhaustion levels are getting higher (as depicted in Figure 4.11 and 4.13). In the case of agent ***A***, the level of reading performance is decreasing despite the agent is having an adequate knowledge and experience to solve the cognitive demanding task due to the low persistence level. Normally, less motivated readers tend to possess a low persistence level leading to reading disengagement (Schnotz et al., 2009). Also, the impact of having a low persistence level can be observed in an agent ***C*** as "reading performance is observed to be low". In contrast for both agents ***A*** and ***C***, the agent ***B*** has improved its reading performance effects due to high level of persistence, low level of cognitive load, and low level of accumulative exhaustion (as depicted in Figure 4.11 and 4.13 respectively). These precursors are essential elements to determine the level of reading performance (Schnotz et al., 2009; Sweller et al., 2011; Aziz, Ahmad, & Hintaya, 2012; Treur, 2011; Choi et al., 2014; Schaffner, Wagner, & Neckel, 2017).

4.4.5 Moderate Effect of Exogenous Factors

For this experimentation purposes, a reader encounters a moderate level of reading task difficulty that imposes a moderate level of cognitive load (see Table 4.7). Figure 4.18 depicts the simulation results for this condition.

Table 4.7

Moderate Effects of the Exogenous Factors

Exogenous Factors	Formalization	Initial Value
Reading task complexity	*Tc*	0.5
Time pressure	*Tp*	0.5
Personal profile	*Pp*	0.5
Task presentation	*Tn*	0.5
Physical environment	*Pe*	0.4
Prior knowledge	*Pk*	0.3
Experience level	*El*	0.4
Reading norm	*Rn*	0.4

The results indicate that reading performance level is increased averagely as compared to its initial values. One of the precursors for this condition is the moderate level of motivation that later lead to the formation of a moderate level of persistence.

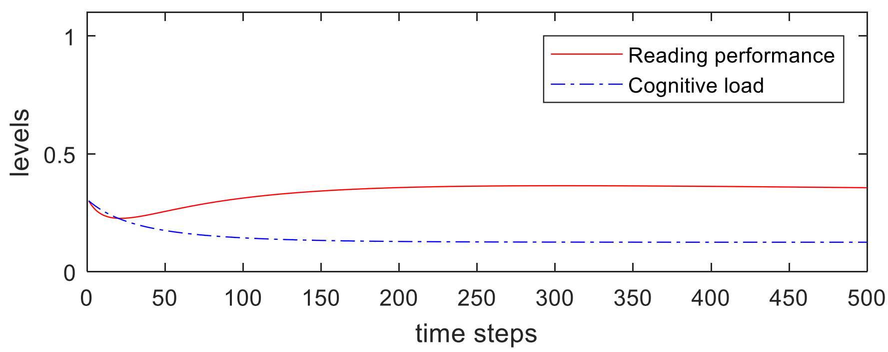

Figure 4.18. Moderate Effects of the Exogenous Factors

Additionally, this condition occurs as the reader is having moderate levels in knowledge, and experiences to curb some difficulties a person has encountered during a reading task. These simulation results are consistent with the previous findings in (Schnotz et al., 2009; Sweller et al., 2011; Treur, 2011; Choi et al., 2014; Schaffner, Wagner, & Neckel, 2017). Appendix E provides additional simulation results related to the cognitive agent model.

4.5 Summary

This chapter provided an insight pertinent to the essential factors and their relationships related to cognitive load and reading performance. There are twenty-eight instantaneous and temporal factors have been identified and discussed. These identified factors were used to construct a causal conceptual design model of a cognitive agent model to understand the mechanism behind cognitive load and reading performance processes. In this chapter, the *Network Oriented Modelling* approach has been used to produce an executable computational cognitive agent model for simulation purposes. It also presented the simulation results of the developed cognitive agent model where several different scenarios for different fictional agents were simulated using a numerical simulation language. The obtained results were found to be in line with the real-world behaviours of cognitive load in cognitively demanding reading tasks. The outcomes from this chapter are related in achieving the first objective of the study. The next chapter (Chapter Five) will cover a comprehensive explanation about the design and development of an ambient agent model to support readers and its simulated behaviours within the Temporal Specification Language LEADSTO.

CHAPTER FIVE
AMBIENT AGENT MODEL DEVELOPMENT AND ROBOT DESIGN

This chapter deals with the steps to design an ambient agent model based on cognitive load and reading performance perspectives and its integration into a reading companion robot. It begins with the discussions on how the cognitive agent model serves as a foundation to design an ambient agent model (Section 5.1) by identifying the underlying support factors to reduce cognitive load and later to increase reading performance (Section 5.2). As a result, three different models were developed (i.e., belief base, analysis model, and support model) (Section 5.3). The constructed model is formalized to generate an executable model for evaluation purposes (Section 5.4). In Section 5.5, results from the ambient agent model behaviours using temporal specification language (LEADSTO) are explained. Moreover, Section 5.6 the ambient agent model is transformed into a set of algorithms to integrate the designed model into an agent (robot) based technology. A brief explanation via simulations on the integrated algorithms of the ambient agent model is presented in Section 5.7. Also, it describes important aspects of reading companion robot (IQRA') design. As a basis to choose the robot interface, a pilot study was conducted to determine the preferred object that was represented as a companion artefact when people read their books as in Section 5.8. Later, the detailed descriptions on the overall design of a reading companion robot (hardware and software components, and human robot interface design) are explained in Section 5.9. Section 5.10 presents the finalized design of IQRA'. Finally, Section 5.11 concludes this chapter.

5.1 Generic Model of the Reading Companion Robot

This section presents a generic model to integrate an ambient agent model of cognitive load and reading performance into a reading companion robot. This underlying model consists of three main interrelated components, namely; (1) Ambient Agent Model, (2) Robot Interface, and (3) Physical Social Gesture. Prior to this, some initial visualization of the high level of abstraction and interaction between these components is depicted in Figure 3.3. The details of the generic model design are shown in Figure 5.1. The solid arrows represent the information exchange between the components, and the dotted arrows indicate that the connected components are possible to occur synchronously. However, for the Model-Based Reasoning Engine component, all dotted arrows represent the encapsulation process of a cognitive agent model within an analysis module.

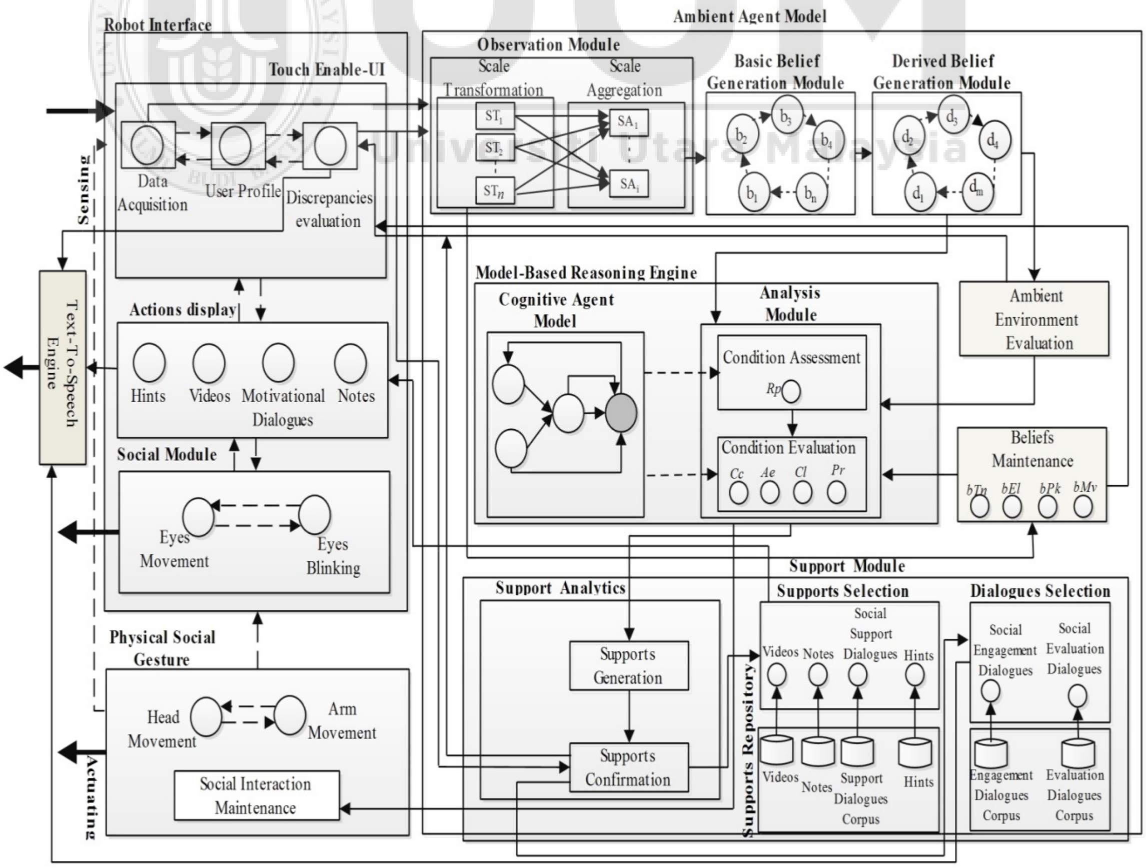

Figure 5.1. The Generic Model of a Reading Companion Robot

Pertinent to the ambient agent model design, Figure 5.1 shows different components that are connected to construct an ambient agent model as a basic computational reasoning process for the reading companion robot. These components are; (1) Belief-Base Model, (2) Model-Based Reasoning Engine, and (3) Support Module. Firstly, the Belief-Base model consists of an observation module, a basic belief module, and a derived belief module.

Secondly, the Model-Based Reasoning Engine is constructed based on the cognitive agent model and its analysis. Finally, regarding create a support module, it entails of support analytics to generate and select an appropriate support action from support selection and dialogues selection modules. Detailed explanations about these interrelated components and its implementation within the ambient agent models are dealt throughout this chapter.

5.2 Cognitive Support Factors and Its Relationships

There are five main factors used to design the support actions within the ambient agent model. Prior to this, several activities were implemented (as mentioned in Chapter Three) such as reviewing psycho-cognitive literature and empirical evidences to acquire these interrelated factors. It is of importance to note that the cognitive agent model (which was designed and developed in the previous chapter) is used as the central reference in discerning those support factors and actions. Table 5.1 summarizes the support actions that have been identified to be integrated within the ambient agent model.

Table 5.1

A Summary of Support Factors within the Ambient Agent Model

No.	Factor	Description	Reference
1	Social Dialogue	A set of motivational talks or praising messages	(Zentall & Morris, 2010; Fasola & Mataric, 2011; Mumm & Mutlu, 2011; Bear, Slaughter, Mantz, & Farley-Ripple, 2017)
2	Short Break	A short pause to discontinue any reading process at certain time	(Henning, Jacques, Kissel, Sullivan, & Alteras-Webb, 1997; Fritz, Ellis, Demsky, Lin, & Guros, 2013; Hunter & Wu, 2016; Kühnel, Zacher, de Bloom, & Bledow, 2017)
3	Similar Task	Identical task that mimics the given reading task.	(Shute, 2008)
4	Suitable Materials	Any additional materials related to the reading task that may contain enough information to solve the task.	(Shute, 2008; Fong, Lily, & Por, 2012)
5	Specific Knowledge	Hints or a piece of information related to the reading task (i.e., additional notes)	(Koedinger & Aleven, 2007; Wu, Hwang, Su, & Huang, 2012; Leyzberg, Spaulding, & Scassellati, 2014)

Later, these support actions will be embedded into the ambient agent architecture as an integrated component in a support module.

5.3 Conceptual Design

The conceptual construct of the model is based on the ambient agent architecture. Therefore, the designed cognitive agent model (domain model) has been integrated in the ambient agent architecture to leverage the functionality as provided by the ambient agent. Figure 5.2 depicts the integration of a domain model (i.e., the cognitive agent model) within the ambient agent architecture to represent the overall human functioning processes of the ambient model of cognitive load and reading performance.

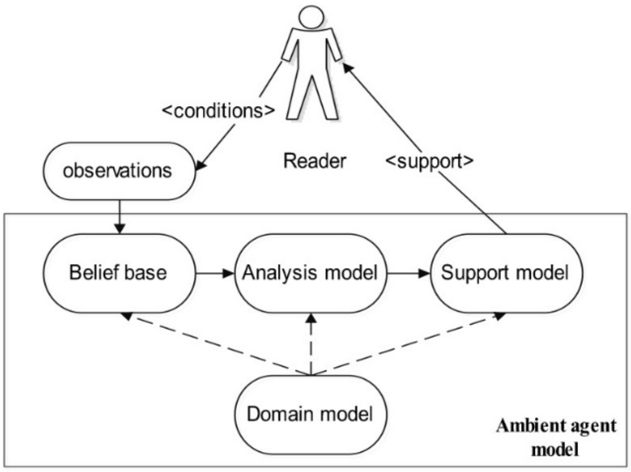

Figure 5.2. Generic Design of an Ambient Agent Model

In Figure 5.2, the solid arrows indicate the information interchange among processes, and the dotted arrows denote the integration process of the domain model within the ambient agent model. The fundamental concept in an ambient agent model comprises three main models. These three models are as follows.

- *Belief-base Model*: To generate primary beliefs (basic and derived beliefs) from the ambient agent's observations.
- *Analysis Model*: To perform analysis of the reader's states and processes by (model-based) reasoning based on observations and the domain model.
- *Support Model*: To generate a set of support actions for the reader by (model-based) reasoning based on observations and the domain model.

The integration of these three models requires a complex interconnected function, which deals with reasoning and analysis processes. The detailed conceptual design of these integrated models that depicts the internal interactions between interrelated models is presented in Figure 5.3. The solid arrows show the information flow between the belief-base and analysis models, and the dotted arrows characterize the activation processes for support actions selections. For the sake of brevity, some abbreviations were introduced in Figure 5.3. These abbreviations are; (1) Belief is represented as "*bel( )*", (2) Observation is abbreviated to "*obs( )*", and (3) Assessment is simplified as "*assess( )*". The next sections provide detailed descriptions about each model within the architecture.

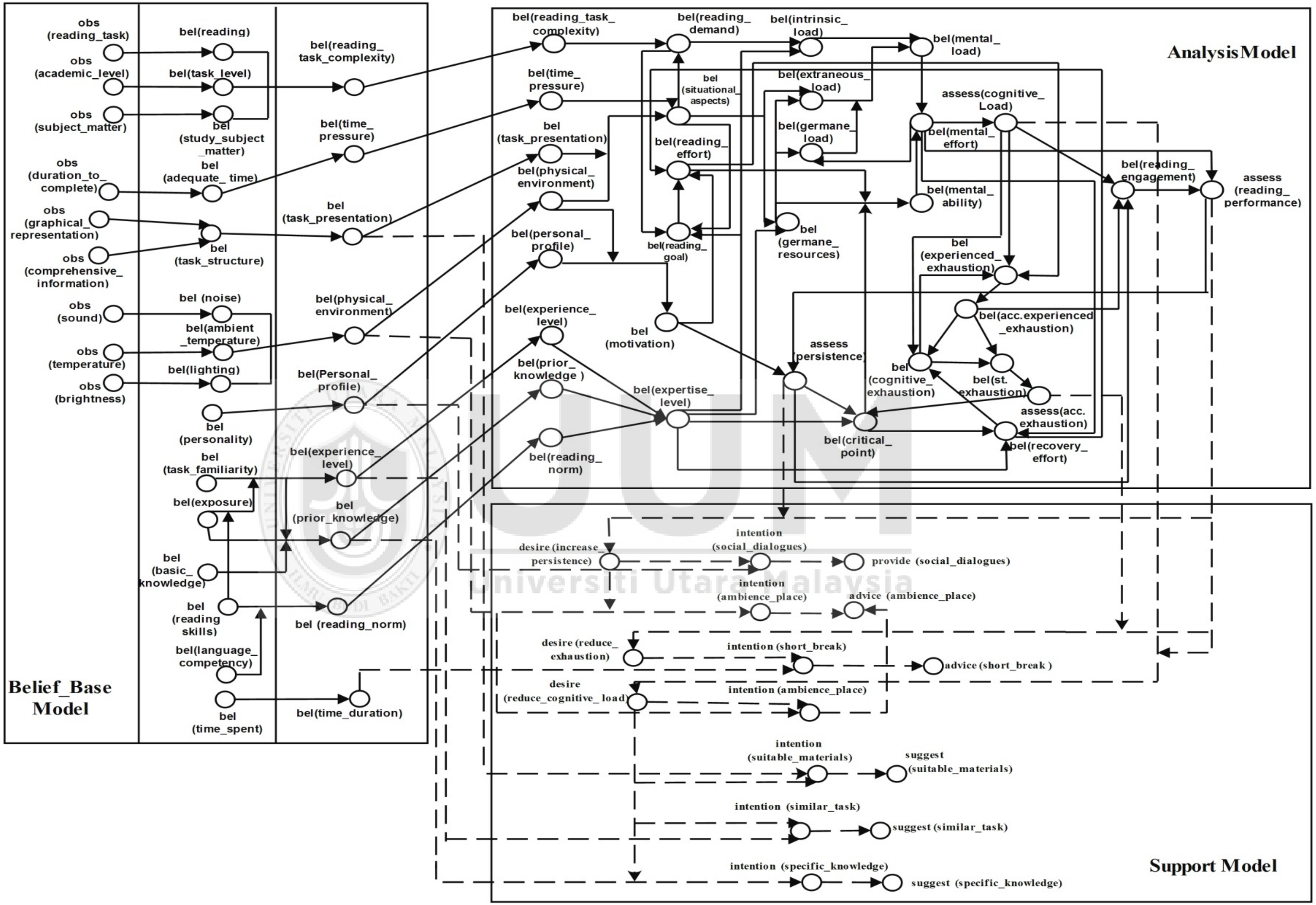

Figure 5.3. The Ambient Agent Model of Cognitive Load and Reading Performance

5.3.1 Belief-Base Model

The primarily goal of belief-base model is to produce a set of initial beliefs (basic and derived beliefs) from the ambient agent's observation pertinent to readers' conditions. From this spectrum, the observed beliefs with its interdependencies can be distinctively known, grouped and integrated (Aziz *et al*., 2010). Basic beliefs refer to a set of direct agent's observation, while derived beliefs refer to the derivations generated based on the domain model. Information about readers' conditions can be observed by utilizing a set of sensors (e.g., as in the case of measuring environment's sound or temperature), or by a set of related questions that reflect each intended observation. There are three different categories of observations, namely; (1) observations about reading task, (2) observations about reading environment, and (3) observations about readers' profiles (characteristics)

One of the advantages to have such a Belief-Base Model (as depicted in Figure 5.4) is it allows future extension of the model. For example, if there is a new method (or sensor) to be used in measuring reading task difficulty, then it can be easily added as a basic belief for a new observation and integrate it with the existing reading task difficulty belief. In addition, another model can make use of this set of related beliefs without having to generate a new one from the beginning.

Moreover, this model allows a direct process to measure a reading task complexity level by a set of related questions about *subject matter* (e.g., mathematics vs. history), *academic level* of the task (e.g., complex questions vs. academic achievement), and *reading task* to allow the agent proceeds with the other related observations (Stodolsky & Grossman, 1995; Nadolski, Kirschner, van Merriënboer, & Wöretshofer, 2005).

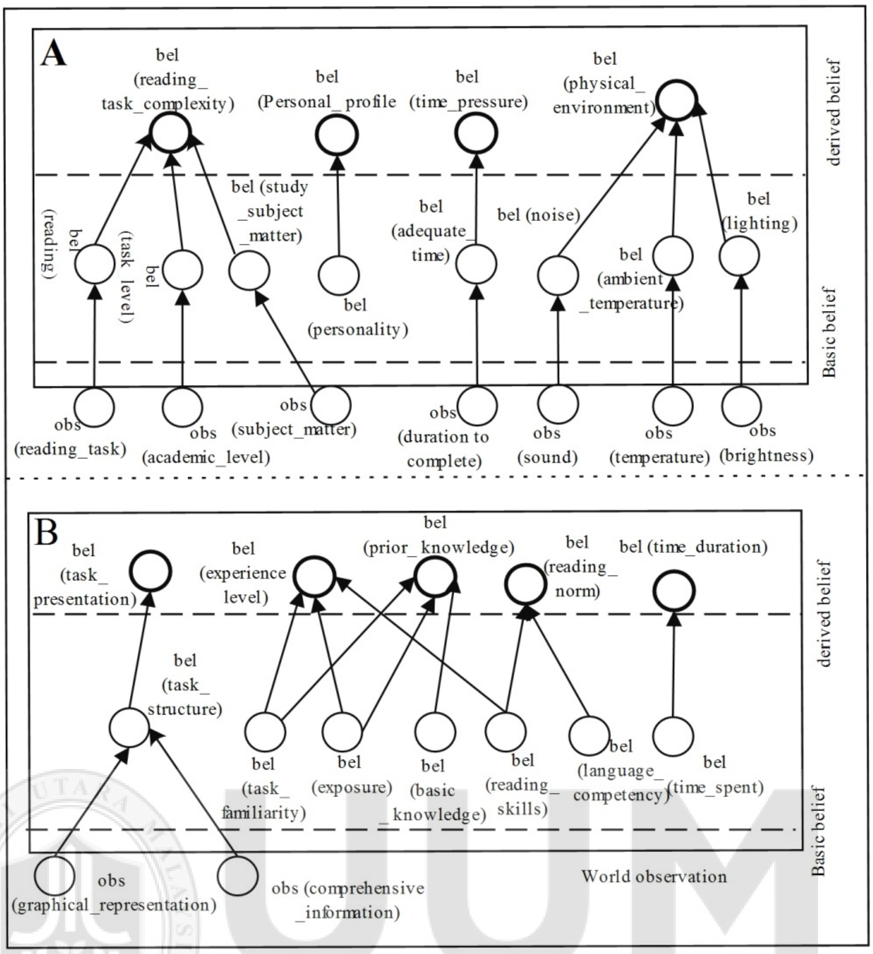

Figure 5.4. Basic and Derived Beliefs in Belief Base.

Another component from the belief-base model is a derived belief on physical environment. For example, the observations about sound, reading room temperature, and brightness levels can be used to generate agent's basic beliefs (Cech, 2016). First, this set of beliefs can be assembled as beliefs about noise level, beliefs about ambient temperature, and belief about intensity of light. Later, the aggregation of these basic beliefs denotes the derived belief of an agent towards assessing any physical environment and its conditions. Another example is for the task presentation and time pressure, these underlying concepts can be determined by observing the task content and the amount of time availability to complete any assigned task.

Similarly, this concept has been applied to generate agent's derived beliefs toward reader's characteristics (i.e., experience level, prior knowledge, and reading norm) where a set of questions related to different aspects is used as a measuring tool to generate the basic and derived beliefs. These aspects are; task familiarity, exposure level, reading skills, language competency, and basic knowledge level. However, not all conditions are necessarily to be observed throughout time in generating the derived beliefs. For instance, reader's personality remains the same within the observation period (Rammstedt & John, 2007).

In addition, a non-stop demanding task is a well-known fact that causes tiredness (which later degrades performance) (Hunter & Wu, 2016; Kühnel et al., 2017), the basic belief on time spent is fixed into the base belief model as an additional component to manage the derived belief about time spent (duration) as a foundation to prompt readers to take a short break.

5.3.2 Analysis Model

The analysis model provides a model-based reasoning mechanism to analyse the dynamics of reader's conditions. These analysed conditions are; *persistence*, *exhaustion*, *cognitive load*, and *reading performance*. It is of importance to note that the design of an analysis model provides an approximation of the equivalent concepts as embedded in the domain model as not all concepts can be directly observed by the ambient agent model.

For example, the levels of *recovery effort* and *critical point* are not something observable in the real world. Therefore, to overcome this challenge, the agent approximates values for the non-observable factors by using a derived beliefs concept.

Figure 5.5 visualizes related concepts from the cognitive agent model that have been integrated as a set of beliefs.

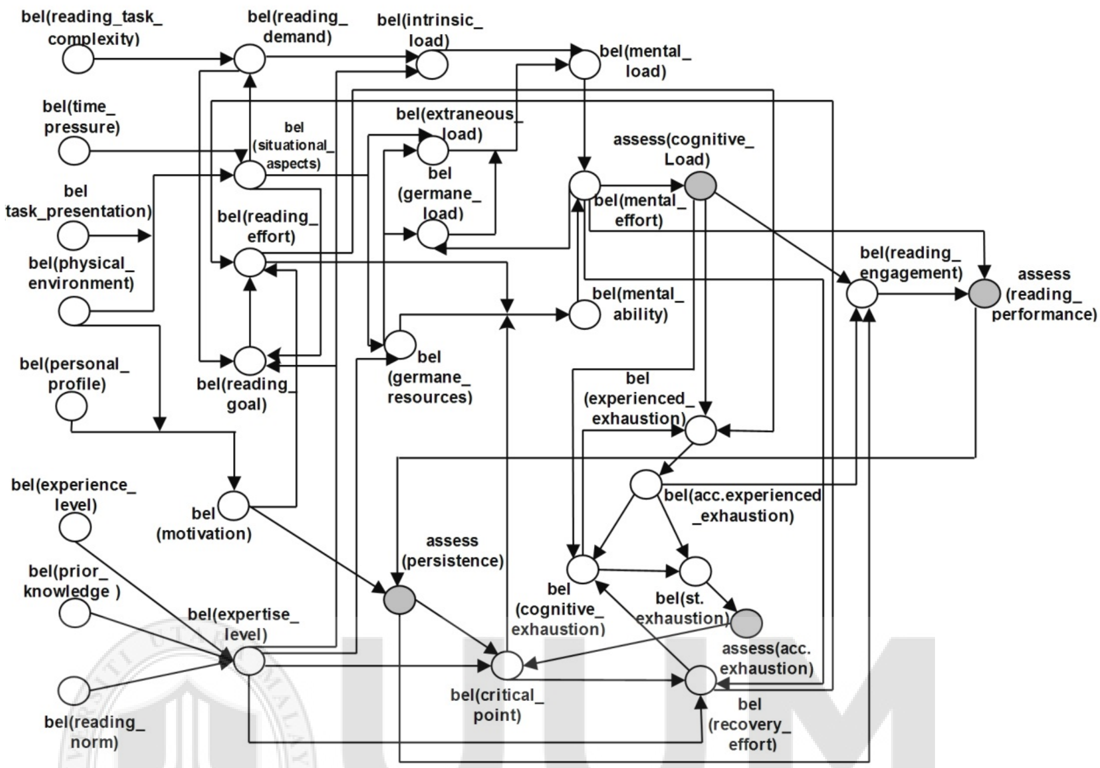

Figure 5.5. Causal Graph of the Analysis Model

The dark grey nodes in Figure 5.5 represent the reader's conditions that an ambient agent needed to generate related support actions, while the white nodes are the derived beliefs. Thus, this approximation functionality allows an agent to monitor related conditions of the readers. For example, as in Figure 5.6, if the assessments for both reading performance (*Rp*) and persistence (*Pr*) are specified with low values (*V1* and *V4*), then the agent model will consider the reader is not performing well due to the low level in persistence. Therefore, the ambient agent's assessment will trigger its "desire" to increase reader's persistence level. Later, the agent's desire will provide specific actions selection in the support model.

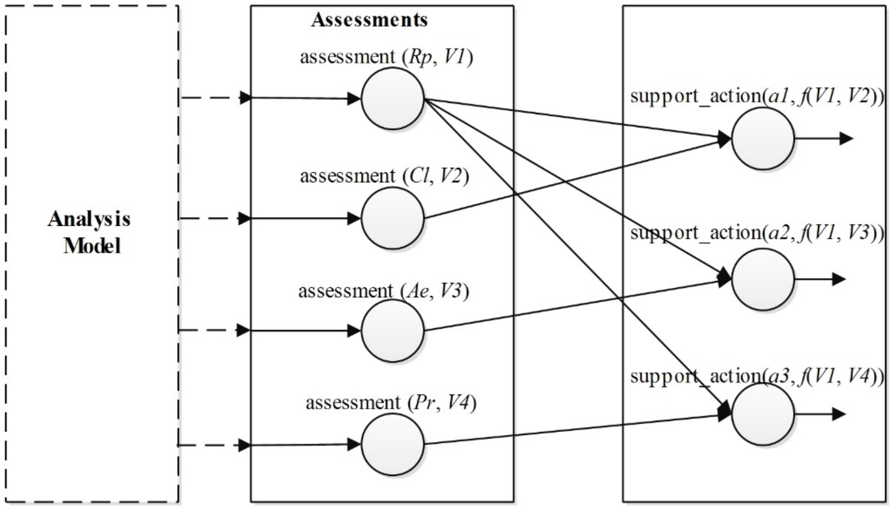

Figure 5.6. Support Actions Selection Based on Analysis Model

Towards this end, the support action *a3* will be determined based on the combination function between persistence and reading performance values (*support_action*(*a3*, *f*(*V1*, *V4*))).

5.3.3 Support Model

Support model is a component that utilizes results from the analysis model. It deals with a set of support actions corresponds to the level of user's conditions. Bosse et al. (2015) describes the importance of a support model within an ambient agent model as:

> ''for an ambient agent to have some beliefs and assessments about the humans' internal state is one thing, but to be of any help, actions are also needed to change or avoid undesirable states''.

As a result from this, based on the assessments and beliefs on reader's conditions, the appropriate support actions are determined to eliminate the potential negative conditions when performing demanding reading tasks. The support actions of the ambient agent are identified from the literature as presented in Table 5.1. For instance, when a reader is experiencing a low level of persistence and it is believed to deter reading performance, then the ambient agent will determine and execute a set of actions to motivate reader by providing friendly social dialogues in term of motivational talks to boost reader's motivation. Consequently, later it will help to increase reader's persistence level.

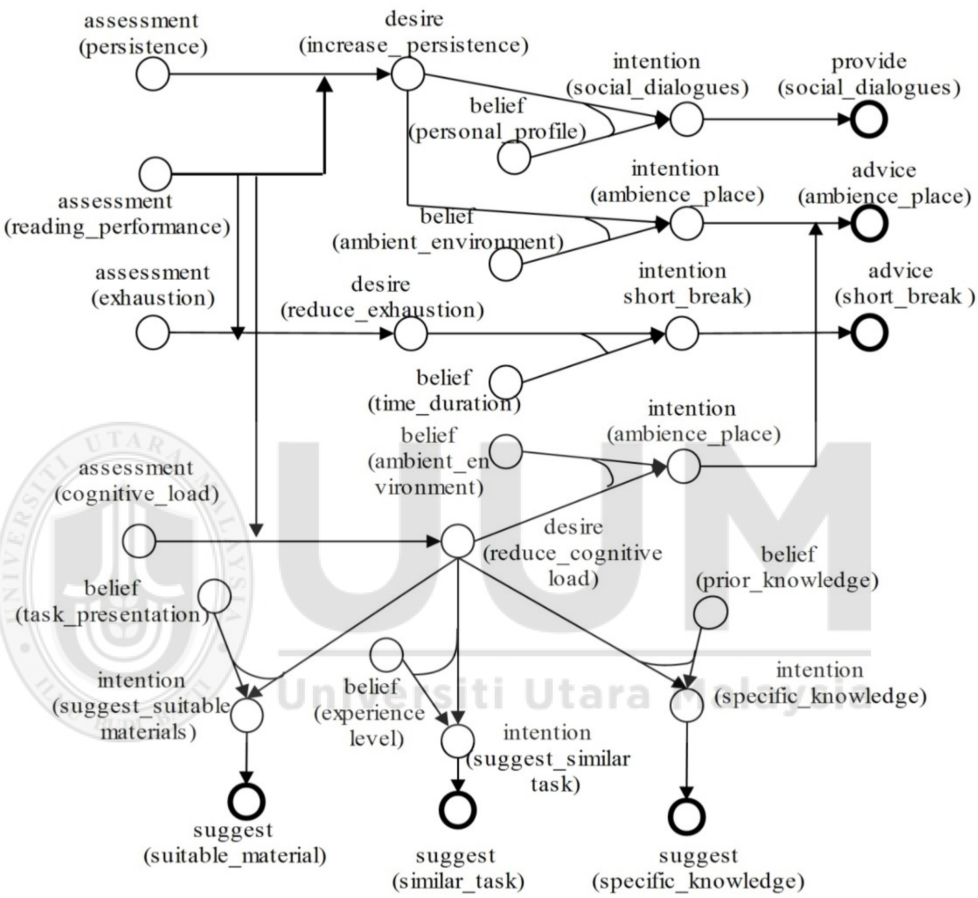

Figure 5.7. Action-Selection Processes within the Support Model

The implementation of Belief-Desire-Intention (BDI) provides an action selection process for optimal support process. From the conceptual level perspective, the implementation of BDI mechanism is depicted in Figure 5.7 where a set of desires to reduce cognitive load and exhaustion (or to increase persistent) and an intention process to support the decision making to improve reading performance were included.

The relationship between desire-intention constructs to perform actions (e.g., R1 ↠ R2) can be described as:

∀N: CONDITION, ∀X: AGENT, ∀T: TASK
R1: desire(X, increase (N)) ∨ desire(X, decrease (N)) ↠
intention (X, provide (T))
R2: intention (X, provide (T)) ↠ perform(X, provide (T))

Note here, the symbol "↠" is an expression of LEADSTO modelling language that means informally "leads to". In this case, the above expression can be read as "the antecedent R1 leads to the consequence of R2".

5.4 Operational Design

As a first step to simulate the ambient agent model, an executable format of the model is developed. In a bid to achieve this, the model is formalized using First-Order Predicate Logic as presented in Chapter Three. The complete explanations about this formalization processes are covered in the next sections.

5.4.1 Ambient Agent Model Ontologies

In this part, a set of formalized logical constructs using First-Order Predicate Logic (FOPL) is built based on specified ontologies. To this end, the formalization of selected properties makes use of sorts. More explanations about these sorts are described in Table 5.2. For example, an ambient agent ability to observe the complexity level of a subject matter can be formalized as:

observed(X: AGENT, subject_ matter(L:LEVEL))

Table 5.2

Sorts Used.

Concept	Sorts	Elements
The medium of an ambient agent to assist readers	AGENT	*{robot, virtual avatar}*
The occurrence of a reading process	STATUS	*{yes, no}*
Measurement for the level of a particular effect such as noise, academic level, and task structure.	LEVEL	*{low, medium, high}*
Individual personality	TYPE	*{positive, negative}*
Reading task complexity	COMPLEXITY	*{easy, moderate, difficult}*
The intensity level of light in reading room	INTENSITY	*{too_bright, adequate, too_dim)*
Duration of the time spent to accomplish a reading task	DURATION	*{short, moderate, long}*
Selected tasks to be performed by an ambient agent	TASK	*{find_an_ambience_place, specific_knowledge, short_break, suitable_materials, similar_task, social_dialogues}*
Room temperature level	TEMP_LEVEL	*{too_warm, neutral, too_cold}*

Thus, the complete ontologies of the ambient agent are specified as follows.

Ontology for Agent's Observations: The observations on reader's condition can be performed through a set of questions or related sensors as inputs for the belief-base model. In this case, the agent requests or detects related inputs about reading task, academic level, subject matter, duration to complete the task, room temperature, brightness, sound level, and the level of information representation associated to the assigned task.

```
observed(X: AGENT, reading_task(S:STATUS))
observed(X: AGENT, academic_level(L:LEVEL))
observed(X: AGENT, subject_matter(C:COMPLEXITY))
observed(X: AGENT, duration_to_complete(D:DURATION))
observed(X: AGENT, sound(L:LEVEL))
observed(X: AGENT, temperature(T:TEMP_LEVEL))
observed(X: AGENT, brightness(I:INTENSITY))
observed(X: AGENT, graphical_presentation(S:STATUS))
observed(X: AGENT, comprehensive_information(L:LEVEL))
```

Ontology for Belief Base: The ontologies of Basic Beliefs that were generated after several observations as follows.

```
belief (X: AGENT, reading(S:STATUS))
belief (X: AGENT, task_level(L:LEVEL))
belief (X: AGENT, study_subject_matter(C:COMPLEXITY))
belief (X: AGENT, personality(T:TYPE))
belief (X: AGENT, adequate_time(D:DURATION))
belief (X: AGENT, ambient_temperature(S:STATUS))
belief (X: AGENT, lighting (I:INTENSITY))
belief (X: AGENT, task_structure(L:LEVEL))
belief (X: AGENT, task_familiarity(L:LEVEL))
belief (X: AGENT, exposure(L:LEVEL))
belief (X: AGENT, basic_knowledge(L:LEVEL))
belief (X: AGENT, reading_skills(L:LEVEL))
belief (X: AGENT, time_spent(D:DURATION))
belief (X: AGENT, reading_competency(L:LEVEL))
```

From the obtained basic beliefs, a set of formalized derived beliefs was obtained as follows.

```
belief(X: AGENT, reading_task_complexity(C:COMPLEXITY))
belief(X: AGENT, experience_level(L:LEVEL))
belief(X: AGENT, task_presentation(L:LEVEL))
belief(X: AGENT, ambient environment (S:STATUS))
belief(X: AGENT, prior_knowledge(L:LEVEL))
belief(X: AGENT, reading_norm(L:LEVEL))
belief(X: AGENT, time_duration(D:DURATION))
belief(X: AGENT, time_presure(D:DURATION))
belief(X: AGENT, personal_profile (T:TYPE))
```

Ontology for Analysis Model: In the analysis model, it is technically possible to directly observe the dynamics of reader's conditions. However, not all the analysis model variables are easy to be observed in the real world. Therefore, a derived belief (d_belief) concept is implemented for such non-observable constructs (refer to Section 5.3.2). A general ontology of this implementation is depicted as:

belief(X: AGENT, d_belief (L:LEVEL))

Therefore, for the derived beliefs on recovery effort and critical point can be expressed as follows.

belief(X: AGENT, recovery_effort (L:LEVEL))
belief(X:AGENT, criticl_point(L:LEVEL))

This formalization is implemented for all non-observable variables or constructs that were presented in Figure 5.5. Another set of ontologies was designed to evaluate the conditions of the reader and triggered based on the agent's evaluation results. These ontologies are as follows.

assessment(X:AGENT, persistence(L:LEVEL))
assessment(X: AGENT, cognitive_load(L:LEVEL))
assessment(X: AGENT, exhaustion(L:LEVEL))
assessment (X: AGENT, reading_performance(L:LEVEL))
evaluation(X: AGENT, persistence(L:LEVEL))
evaluation(X: AGENT, cognitive_load(L:LEVEL))
evaluation(X: AGENT, exhaustion(L:LEVEL))

Ontology for Support Model: The support model ontologies are grouped in a form of Belief-Desire-Intention (BDI) and performed atomic logic. This set of ontologies utilizes BDI architecture mechanism in processing the interplays between the causal and effect relationships. Generally, the overall processes of an ambient agent architecture in generating and selecting support actions is depicted in Figure 5.8. As a first step, an agent observes user's condition as inputs to generate its new beliefs based on the current beliefs and inputs (as discussed in Section 5.3.1) and this is achieved by a Belief Revision Function (BRF). Based on the generated beliefs and model-based reasoning mechanism, the agent will be able to evaluate and analyse user's dynamic conditions and produce a set of desires based on the analysed conditions (as explained in Section 5.3.2). Once the agent has determined its beliefs and desires about a particular condition, then the agent selects the most appropriate action to be performed based on its current intention (as discussed in 5.3.3).

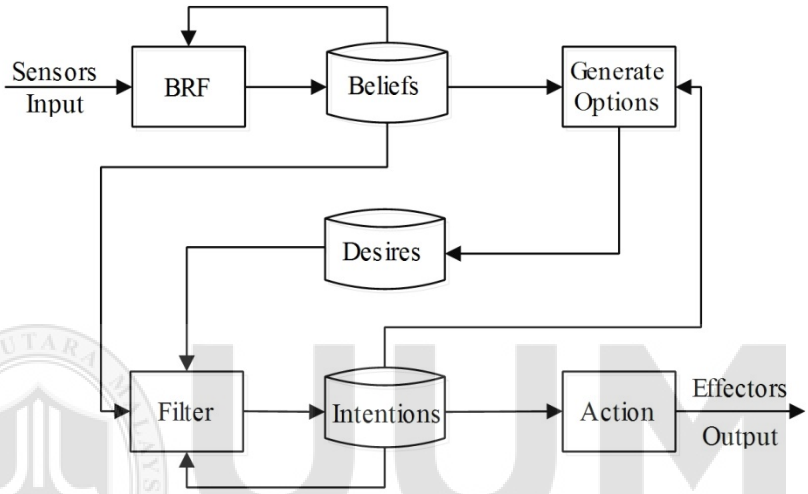

Figure 5.8. The Practical Reasoning Process in a BDI Agent

In this study the ambient agent utilizes the aforementioned concept in providing support actions to readers where a set of support ontologies were designed to serve its purpose. These ontologies are as follows.

belief(X:AGENT, persistence(L:LEVEL))
belief(X: AGENT, cognitive_load(L:LEVEL))
belief(X: AGENT, exhaustion(L:LEVEL))
desire(X:AGENT, increase (N:CONDITION))
desire(X: AGENT, reduce (N:CONDITION))
intention(X:AGENT, provide(T:TASK))
intention(X:AGENT, advice(T:TASK))
performed(X:AGENT, provide(T:TASK))
performed(X:AGENT, advice(T:TASK))
performed(X:AGENT, suggest(T:TASK))

5.4.2 Knowledge Specifications

Knowledge specifications make use of the completed ontologies as a design construct to generate a set of dynamics temporal specifications. These temporal specifications allow the ambient agent to reason about readers' conditions by using the forward reasoning method as a basis for beliefs generation (Bosse et al., 2007). This approach follows the time sequence and causality in generating a set of new beliefs from previous properties. In general, the ambient agent functionality can be described in three actions; (1) beliefs generations in the belief-base, (2) assessments and evaluations of the reader's condition from the analysis model, and (3) actions to help the reader from the support model. Note here, the rules of the ambient agent are implemented in the hybrid language toolkit, LEADSTO. The LEADSTO tool is utilized to generate simulation traces to represent the behaviour of the real-world model. Due to a large number of possible generated rules and specifications based on the agent's ontologies, the followings are selected temporal rules and specifications to be used in observing environment, evaluating conditions, and providing supports for readers.

RL1: Generating Basic Belief on Task Presentation

When the ambient agent observes that the reading task contains inadequate information to be comprehended (e.g., no graphical explanations /materials), then the ambient agent believes that the reading task materials are not well-presented.

> observed(agent, graphical_presentation(no)) ^ observed(agent, comprensive_information (low)) ↠ belief(agent, task_structure (low))

RL2: Derived Belief on Time Duration

When the agent believes that the reader has endured extended duration for the reading task, then the agent believes that the time spent is long.

> belief(agent, time_spent(long)) ↠ belief (agent, time_duration(long)).

RL3: Evaluation on Exhaustion Condition

When the ambient agent assesses reader is exhausted and no longer performing well, then the agent evaluates the exhaustion level stage as high.

> assessment(agent, exhaustion(high)) ^ assessment(agent, reading_performance (low)) ↠ evaluation(agent, stage(exhaustion, high))

RL4: Intention to Advice for Short Break

When the ambient agent desires to reduce the level of exhaustion by giving advices (e.g., for a short break) and the agent believes that the time is still available (adequate), then the agent will have an intention to advice the reader for a short break.

> desire(agent, reduce(exhaustion)) ^ belief(agent, time_duration(long)) ↠ intention(agent, advice(short_break))

RL5: Action to Advice for Short Break

When the agent intends to advice the reader to get a short break, then the agent will advise the reader for a short break.

> intention(agent, advice(short_break)) ↠ performed(agent, advice(short_break))

5.5 Simulation Results for Ambient Agent Model

The ambient agent model was designed and formalized (in terms of First-Order Logic specifications) after all concepts in a cognitive agent model were evaluated. After these formal specifications are coded (using LEADSTO simulator tool), the reading task simulation is executed using 500 time-steps to represent the four-hours monitoring processes. This determined duration is consistent to the real-world experiments that performing a cognitive task for more than three hours creates impacts on task performances based on the effects on motivation, exhaustion, and cognitive load (Möckel, Beste, & Wascher, 2015).

5.5.1 High Level of Cognitive Load

The condition of having a high level of cognitive load occurs when a reader is performing a demanding reading task that requires large amount of efforts and those acquired efforts exceed reader's resources to cope. In order to provide adequate support actions, the agent must capable to observe important conditions such as; difficulties of a subject matter (i.e., meant for a higher academic level), distraction in environment (e.g., due to an extreme level of sound, temperature (i.e., too cold/ hot) and brightness (i.e., too dim/bright)).

Another condition such not well-presented task (the assigned reading task is not presented with a set of comprehensive and graphical information. In addition, lack of knowledge and experience to solve certain assigned tasks also contributed to the formation of a high cognitive load level. By analysing all possible conditions, the agent will be able to evaluate reader's cognitive load throughout time and provides an appropriate action if all beliefs hold true. Figure 5.9 depicts the results in a form of simulation traces to illustrate how a reader experiences a high cognitive load level and when the agent performs related support actions.

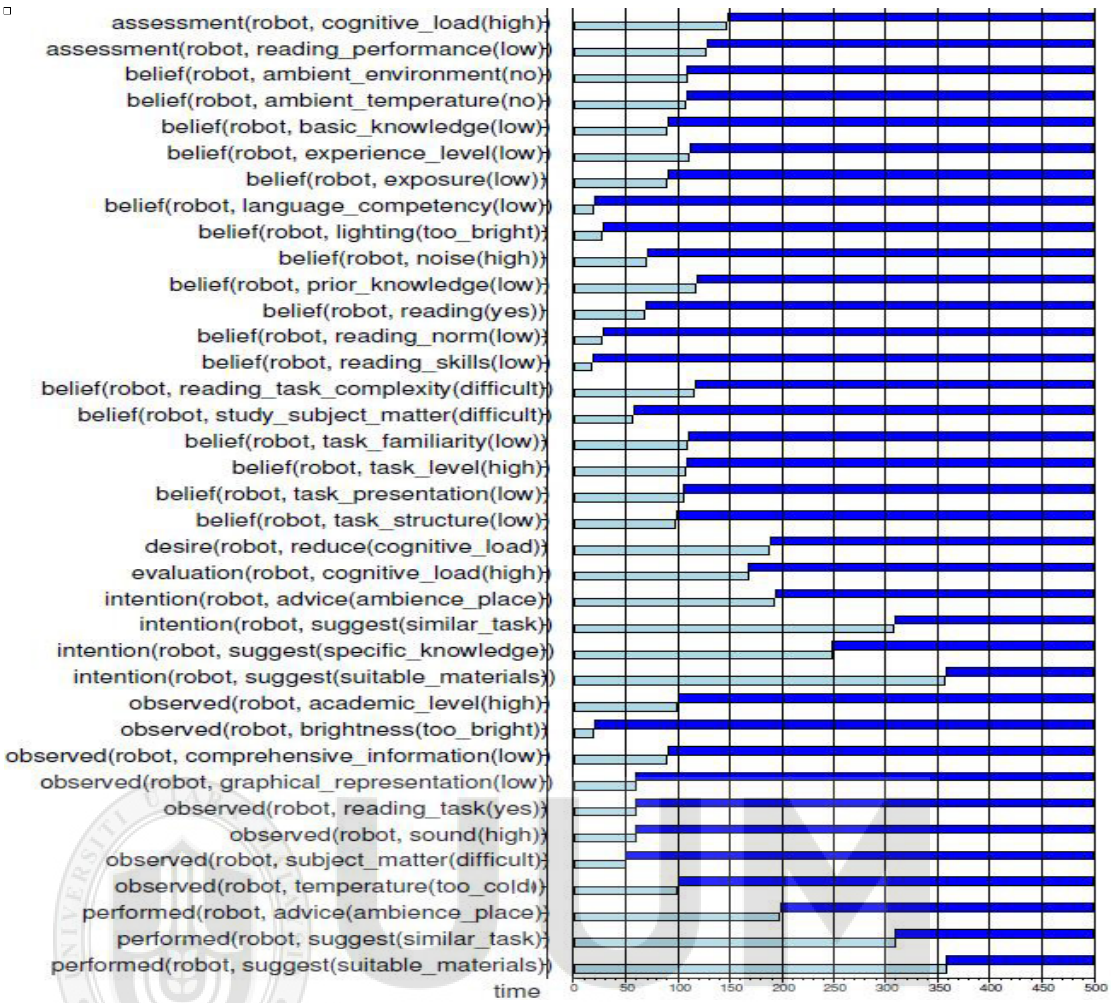

Figure 5.9. Simulation Traces for a High Cognitive Load Level and its Support Actions

As a first step, the agent evaluates the conditions of reading performance and cognitive load levels. For example, if both conditions were evaluated as “not preferred”, then the agent generated its desire to alleviate the effect of experienced cognitive load. Correspondingly, all beliefs related to the occurrence of cognitive overload (i.e., beliefs about task presentation, prior knowledge, experience level, and physical environment) will be evaluated and if they hold true, then the agent provides a set of appropriate support actions. The results from these belief generation and support assignment processes are shown in Figure 5.9.

5.5.2 High Level of Exhaustion

In many ways, if a person has been working on a certain task for more than two hours, it will deteriorate human's capacity, thus reducing working capability at the same pace due to exhaustion (Lorist et al., 2000; Csathó, van der Linden, Hernádi, Buzás, & Kalmar, 2012). In this case, the agent will be able to observe the time spent while performing the task. Prior to that, the agent monitors reader's current reading performance and accumulative exhaustion levels.

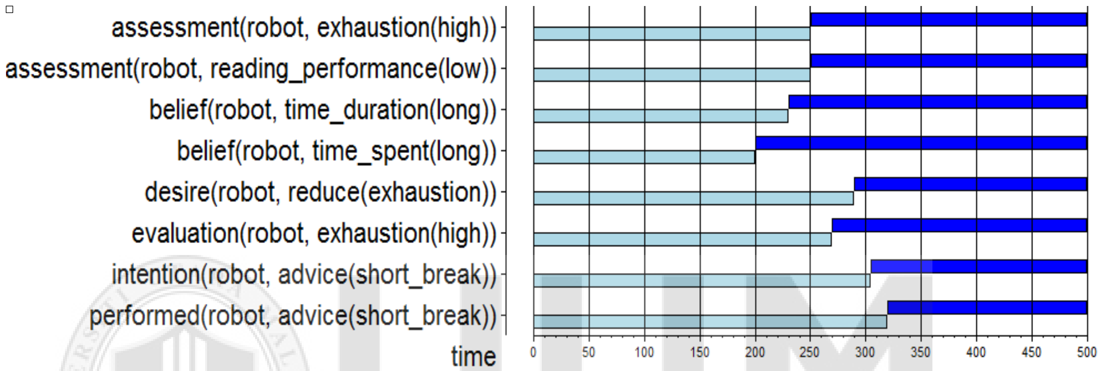

Figure 5.10. Simulation Traces of High Accumulative Exhaustion (*Ae*)

Based on agent's observation and its assessments, an appropriate support action will be administrated to reduce the unwanted conditions (i.e., advising the reader for a short break). Figure 5.10 depicts the simulation traces for a reader that is experiencing a high level of exhaustion with its appropriate support actions.

5.5.3 Low Level of Persistence

Many previous findings shown that persistence level plays an essential role in empowering a reader with the ability to stay engaged during performing demanding cognitive tasks (Schnotz et al., 2009). For example, in many occasions, reading to grasp new knowledge requires a high level of persistence. Thus, an appropriate action should be taken by the agent when a reader experiences a low persistence level and it is about to disengage from the reading task. This condition will become apparent when the agent observes the reader has a negative personality (e.g., neurotic personality). Normally, a reader with this type of personality tends to experience low level of motivation compared to others (e.g. openness, agreeableness) (Daitkar, 2017). In this model, this support will be provided when the agent evaluates both of reading performance and reading persistence are low (as in Figure 5.11).

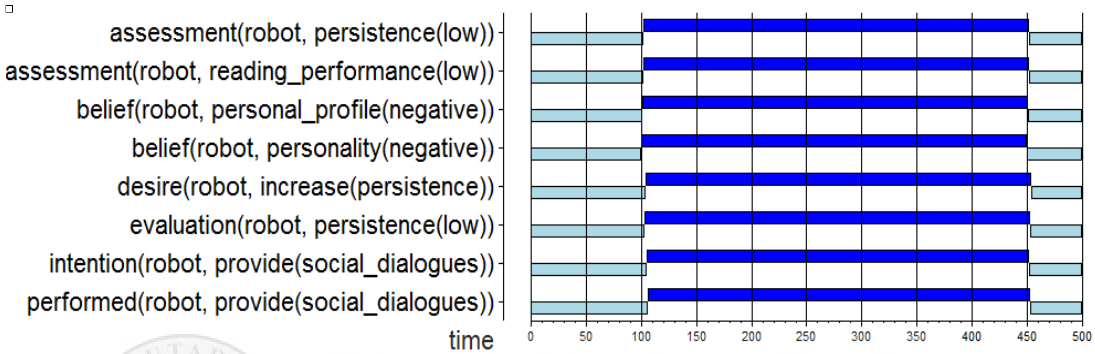

Figure 5.11. Simulation Traces of Low Persistence (*Pr*)

Based on agent's observations and assessments, a social dialogue (i.e., in a form of praises or motivational talk) will be prompted to motivate the reader that later curb the unnecessary conditions. First, the agent generated desire to increase the level of persistence after persistence and reading performance evaluation. Moreover, due to the agent's belief about personality, then the agent tends to have an intention to provide a social dialogue to curtail the possible ramifications of having a low persistence level (e.g., disengagement).

5.5.4 Non-conducive Learning Environment

The non-conducive environment contributes majorly to increase cognitive load due to the extreme extraneous load imposes on readers (Choi et al., 2014; Cech, 2016). In the same vein, a non-conducive learning environment plays an important role in maintaining reader's persistence level due to its impact on a motivation level. For example, reading in a comfortable environment will promote a better motivation perspective and thereby persistence will stay high through the reading period. Thus, to overcome the resulted cognitive load level, the ambient agent will observe the unwanted condition (i.e., non-ambient environment) related to the learning environment for support generation purposes.

For this scenario, the agent observes different conditions related to learning environment, namely; brightness level, sound level, and temperature level. These observations enable the agent to generate its belief about reading environment (i.e., *ambient environment*). Moreover, if the agent's evaluation about persistence and reading performance levels holds true, then the agent generates a desire to increase persistence level. This desire and agent's belief generate intention to provide an advice for making the reading environment more convenience (e.g., reduce noise level or move to another room). Figure 5.12 presents the simulation traces of low persistence condition with its support related to learning environment.

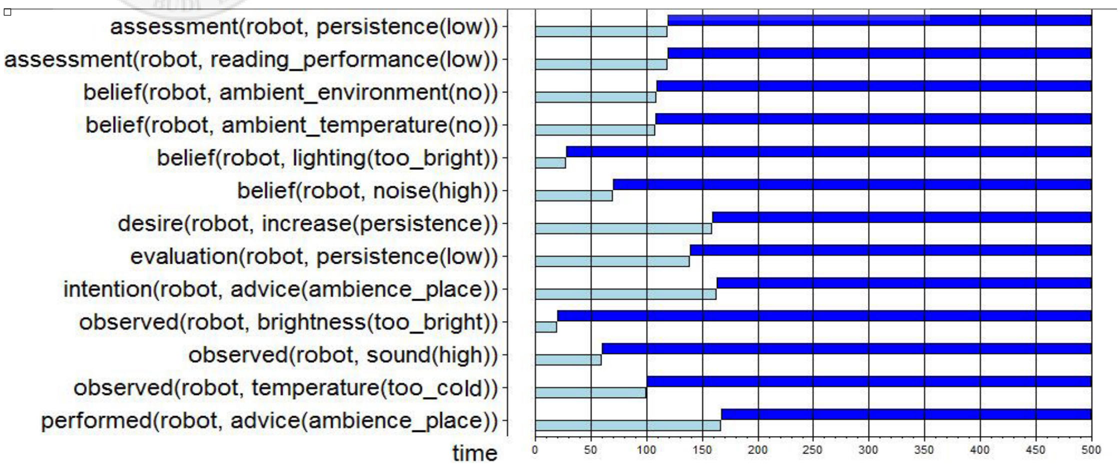

Figure 5.12. Simulation Traces of a Non-conducive Learning Environment

Appendix E provides thorough simulation traces for a number of related cases.

5.6 Ambient Agent Model Integration

At this stage, once the ambient agent model has been developed, it is important to design a specific procedure to utilize its implementation in real-world. To achieve this end, an integration algorithm has been developed to serve as a reasoning engine for the model. This integration algorithm serves as an underlying analytical tool in monitoring and analysing reader's performance. Moreover, it provides a blueprint in integrating the entire computational and physical components (hardware and software) to support the entire functionalities for the companion robot. As a result, an appropriate support action (as stored in support repository) will be relayed to readers. Figure 5.13 displays the required components in integrating the designed ambient agent model into an agent (robot) based technology.

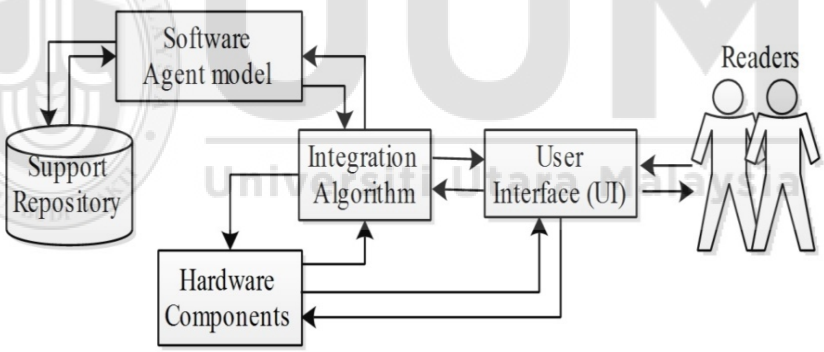

Figure 5.13. Integration Components of an Ambient Agent Model

In the integration algorithm component, the generic flow chart of the integration processes is shown in Figure 5.14. It consists of six related components, namely; (1) input initialization, (2) environmental evaluation, (3) reader's monitoring phase, (4) evaluation mode, (5) support mode, and (6) external interruption (force-stop mode).

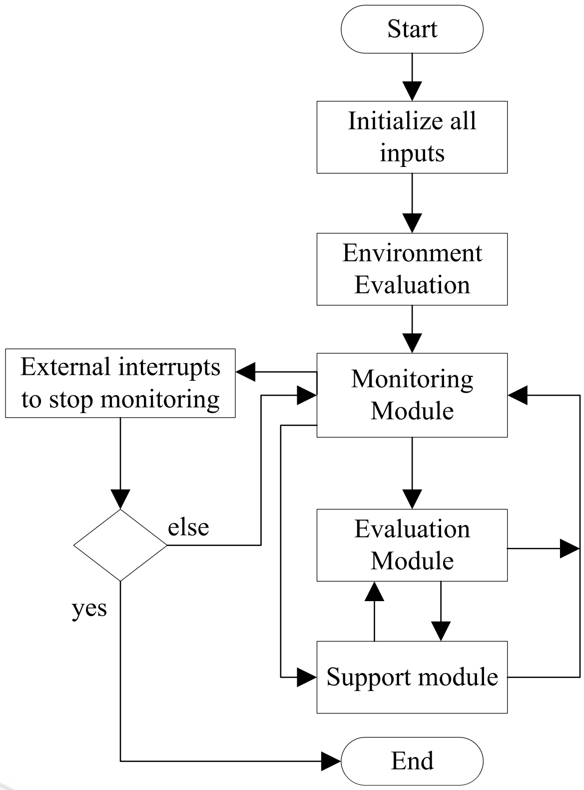

Figure 5.14. General Steps in the Integration Algorithm

For the sake of brevity, the integration algorithm can be divided into a set of sub-algorithms. These algorithms are designed based on important guidance as highlighted in Cormen (2009). It is important to note that these algorithms are mainly controlled by the monitoring module where most of the reader's condition analysis is implemented. In addition, it serves as the core element for the overall integration process. Detailed descriptions related to the aforementioned integration algorithms are discussed in the following sections.

5.6.1 Input Initialization

In the beginning, the agent will initiate all of its observations to generate basic and derived beliefs related to reader's conditions. For example, when the agent observes the level of sound in the room, the basic belief about the noise level is evaluated.

observation(agent, sound(level))↠ basic_belief(agent, noise(level))

At the end of the agent's observation processes, all the derived beliefs will be assigned and later to be propagated to another component within the integration algorithm (as depicted in Figure 5.14). Table 5.3 presents some formal representations and its nomenclatures for some important concepts used in the algorithms development.

Table 5.3

Formal Specifications

Descriptions	**Specification**
If agent *A* observes *x* condition then the agent will compute basic belief on *y*.	$o(A, x) \twoheadrightarrow b(A, y)$
If agent *A* believes on *y* then the agent will compute derived belief on *z*	$b(A, y) \twoheadrightarrow d(A, z)$
Agent *A* assesses the level of *x* whether it is greater or equal to *x* threshold	$a(A, greater(x, x_t))$ $a(A, equal(x, x_t))$

The overall formal representations for the integration algorithms development are presented in Appendix C.

5.6.2 Physical Environment Module

In general, reading environment is a crucial factor and it has considerable effects on reading performance (Choi et al., 2014; Cech, 2016). Hence, through a set of computational processes, the agent will evaluate the reader's environment (i.e., physical environment based on the ambient agent model) prior advancing to the next stage. The computational processes were shown in Algorithm 5.1.

Algorithm 5.1: Environment Module

```
Input: d(A, Pe)
Output: ambient environment.
Start
  Initialization
    Pet, such that 0 ≤ Pet ≤1
    Ab, such that Ab← false, i← 1
  Evaluate physical environment
    Do
      if (d(A, Pe >= Pet))
        then s(A, Cp_i)
            if (Cp_i))
              then v(A, Am)
                   u(A, Pe)
            else s(A, Cp_i+1)
            if (Cp_i+1)
              then v(A, Am)
                   u(A, Pe)
            else Ab← true
      else Ab← true
    While (Ab)
MonitoringMode ( )
End
```


First, the algorithm works to analyse the derived belief of an agent towards its physical environment, $d(A, Pe)$. Next, if the observed condition (value) is greater than the threshold *Pet* ($d(A, Pe >= Pet)$), then the agent will prompt a confirmation message to inform that the room is not suitable enough for a reading process to take place $s(A, Cpi)$, otherwise a monitoring mode will be triggered. Therefore, when the condition status has been confirmed, the agent will advise the reader to perform some necessary actions to diminish any potential disturbances caused by the environment $v(A, Am)$. Next, the derived belief about the environment will be updated based on those new acquired settings. Furthermore, if the reader does not confirm the condition, then the agent will also display a confirmation message about the current state of the environment. All of these steps are continuously monitored unless the reader has decided to change the environment, or she/he feels comfortable with the current conditions. The flowchart of this module is shown in Appendix D.

5.6.3 Monitoring Module

The monitoring module acts as a primary role of the overall integration process to take place. Within this module, most of the analysis process is executed. The ambient agent model (i.e., the reasoning engine of the intelligent agent) will be synchronized and executed concurrently for computational instantaneous beliefs and temporal assessments based on the derived beliefs and initial values as mentioned in Section 5.5.1. In the end, this module evaluates a reading performance at the predetermined time intervals.

The detailed process of a monitoring module includes:

I. ***Activate_evaluation_mode*** activates when the reading performance (*Rp*) is continuously decreasing ($dRp/dt < 0$) and it is lower than threshold *Rpt*. This can be seen in Figure 5.1 under an Analysis Module.

II. ***Provide_praising_dialogue*** is essential for positive progression $p(A, Pg)$ if the reading performance is increasing ($dRp/dt > 0$) and approaching the threshold ($(Rpt - Rp) > mp$). Similarly, it holds true for maintaining the performance $p(A, Pm)$ when changes in reading performance level is greater than threshold ($dRp/dt > 0$ and $Rp >= Rpt$). The *mp* is defined as the maximal progression value which represents a small positive number, for example 0.05.

III. ***Perform_consistent_checking f*(*A*, *Cc*)** aims to ensure the model reflects real conditions experienced by readers. By doing this, the agent will prompt a confirmation screen $s(A, Cr)$ to evaluate readers whether they have experienced high cognitive load level $e(r, Hcl)$, high level of exhaustion $e(r, Hae)$, or low persistence level *e(r, Lpr)* prior to the activation of the intervention part. If readers confirm the evaluation results, then the agent will intervene to alleviate the reading experienced conditions. In this case, support modules will be triggered to provide related assistantship (i.e., *SupportCL( ), SupportPr( ), or SupportAe( )* respectively). This consistent checking process is continually occurred at the predetermined *Z* time interval.

IV. ***Activate_support_exhaustion* (*SupportAe( )*)** invokes when the agent beliefs that the reader has reached a certain level of maximum duration of reading (based on predefined limit) (*Max_time)* and the reader should get a well-deserved short break.

These aforementioned actions within the monitoring module are expressed in Algorithm 5.2.

Algorithm 5.2: Monitoring Module

```
Input: initial values and derived beliefs.
Output: evaluated level of reading performance.
Start
  Initialization
    Rpt, such that 0 ≤ Rpt ≤1, c←2, d←2, k←2
  Repeat every time point t
  Compute all instantaneous beliefs and temporal assessments at time step tp
    For every x, a(A, Rp) such that x ∈ tp
      if ( time_step/x = c-1)
        then if (dRp/dt ≤ 0 ∧ Rp≤Rpt)
               then EvaluationMode( )
            c ←c+1
    For every y, a(A, Rp) such that y>x, y ∈ tp
      if ((time_step/y) = d-1)
               then if ((dRp/dt> 0) ∧ (Rpt– Rp> mp))
                then p(A, Pg)
            if (dRp/dt >= 0 ∧ Rp >= Rpt)
                then p(A, Pm)
            d ←d+1
    For every z, f(A, Cc) such that z > y, z ∈ tp
      if ( (time_step/z) = k-1)
        then s(A, Cr)
            if e(r, H_cl)
              then SupportCL( )
            else if e(r, L_pr)
               then SupportPr( )
            else if e(r, H_ae)
                then SupportAe( )
        k←k+1
    if time_spent ≥ Max_time
        then SupportAe( )
  tp←tp +1
  ts ← ts + t
  Until reader stop monitoring
End
```

For further understandings, Appendix D covers the detailed flowchart of this algorithm.

5.6.4 Evaluation Module

The evaluation module (*EvaluationMode( )*) will be activated when the reader's performance is below than the assigned threshold value *Rpt* (i.e., the threshold value of reading performance is predetermined based on the cognitive agent model (*Rpt*=0.5)). This module is primarily designed to identify potential factors that may hamper reading performance. Moreover, it endows the agent an ability to decide which detrimental condition should be avoided to improve reading performance. Algorithm 5.3 shows the important stages for evaluation module.

Algorithm 5.3: Evaluation Module

Input: *a(A, Cl), a(A, Pr), a(A, Ae), a(A, Rp)*.
Output: determine the conditions that require support.
Start
    Initialization
        Clt, such that $0 \leq Clt \leq 1$.
        Aet, such that $0 \leq Aet \leq 1$.
        Prt, such that $0 \leq Prt \leq 1$.
    if $(a\ (A,\ dAe/dt \geq 0) \wedge\ a(A,\ Ae \geq Aet))$
        then *SupportAe ( )*
    else
        if $(a(A,\ dPr/dt \leq 0) \wedge\ a(A,\ Pr \leq Prt)))$
            then *SupportPr ( )*
                if $(a(A,\ \mathrm{d}Cl/dt \geq 0) \wedge\ a(A,\ Cl \geq Clt))$
                    then *SupportCL( )*
        else $(a(A,\ \mathrm{d}Cl/dt \geq 0 \wedge a(A,\ Cl \geq Clt))$
            then *SupportCL( )*
End

For example, if the agent evaluates the exhaustion level is continuously increasing $(a(A,\ dAe/dt \geq 0))$ between t_n and t_{n+1} (two intervals) and it is exceeding the threshold *Aet*, then the support exhaustion module *SupportAe( )* will be triggered, else the cognitive load and persistence conditions will be analysed for necessary support provision. In this case, the agent progressively evaluate reader's persistence level, and if it is constantly decreasing $(a(A,\ dPr/dt \leq 0))$ between t_n and t_{n+1} time interval and lower than the threshold value *Prt*, then the support persistence module *SupportPr( )* will be triggered. Similarly, the agent evaluates the cognitive load level and if it is continuously increasing $(a(A,\ \mathrm{d}Cl/dt \geq 0))$ between t_n and t_{n+1} and exceeding the assigned threshold *Clt*, then the cognitive support module will be triggered to ease the undesired impact of cognitive load *SupportCL( )*. The thresholds *Clt*, *Aet*, and *Prt* values were assigned based on the experimental results (0.4, 0.4, and 0.5 respectively). For additional explanations, the complete flowchart for Algorithm 5.3 can be found in Appendix D.

5.6.5 Support Modules

The assignment to deliver the right support is, based on the agent's assessments and evaluations, resulted from the monitoring and analysis processes (refer to Figure 5.1). In this case, three types of supports will be generated to reduce the negative impact of cognitive load and its consequences, namely; Support for Exhaustion (*SupportAe( )*), Support for Persistence (*SupportPr( )*), and Support for Cognitive Load (*SupportCL()*). For example, if the agent evaluates a reader experiences potential high level of getting exhausted, then Support for Exhaustion procedure will be triggered (i.e., *SupportAe()*). In many conditions, this support process is very crucial as exhaustion will always deteriorate overall reading performances.

A) Persistence Module

Low persistence level is often positively correlated to the percentage in reading focus and continuation (Schnotz et al., 2009). However, with the administered motivational talks (short talk) it will later improve an overall reader's persistence. In this module, the agent will trigger a motivational talk support *p*(*A*, *Mt*) to be activated if a low persistence level has been observed. This concept has been implemented due to the impact of motivation as it plays an important role in determining the level of reader's persistence (Schnotz et al., 2009; Mills, Bosch, Graesser, & D'Mello, 2014). The algorithm to detect and provide motivational talks is presented in Algorithm 5.4.

Algorithm 5.4: Persistence Module

```
Input: d(A, Mv)
Output: p(A, Mt)
Start
  s(A, Cs_i)
    if (Cs_i )
      then p(A, Mt)
           u(A, d(Mv))
    else s(A, Cs_{i+1})
           if (Cs_{i+1})
              then p(A, Mt)
                   u(A, d(Mv))
End
```

In the beginning, a confirmation message *s*(*A*, *Csi*) will be prompted by an array of selected motivational talks *p*(*A*, *Mt*). The agent then will re-evaluate the condition based on a confirmation from the reader. Moreover, the derived belief on motivation will be revised when the reader receives a set of selected motivational talks as in *u*(*A*, *d*(*Mv*)).

B) Exhaustion Module

The evaluation module aims at providing short break support actions (e.g., providing advices to relax, listen to music, or even walking for a short distance) based on agent's assessments from the monitoring and evaluation modules. Such support actions can be explained in two folds. First, when the agent observes and beliefs the exhaustion level is continuously increasing and exceeding the assigned threshold (as stated in Section 5.5.3). Second, when the time has been spent for the reading task is exceeding the predefined time (e.g., more than two or three hours in a row). These two conditions are represented in a monitoring module. Algorithm 5.5 explains the process in providing short break support actions. Once this module is triggered, the agent will prompt readers by displaying a confirmation message *s*(*A*, *Cei*). This message aims to rectify readers about their current estimated exhaustion level. Thus, the short break advice *v*(*R*, *Sb*) will be provided if the reader has been detected as have experienced exhaustion. Otherwise, the second confirmation will be prompted to verify the experienced exhaustion level. Furthermore, when these support actions are triggered, the agent has to restore its monitoring process based on the baseline settings (i.e., time spend (*ts*) will be restored to zero at *tp*=1).

<u>Algorithm 5.5: Exhaustion Module</u>

```
Input: ts, tp.
Output: To provide short break actions
Start
  s(A, Ce_i)
    if (Ce_i)
      then v(A, Sb)
    else s(A, Ce_i+1)
        if (Ce_i+1)
          then v(A, Sb)
  tp← 1
  ts ←0
End
```

For further explanations, the flowchart that mapped these steps (exhaustion module) can be found in Appendix D.

C) Cognitive Load Module

Within this module, readers with a cognitive overloaded condition will be supported by providing different approaches based on particular derived beliefs. These types of support can be viewed as;

- Recommends a similar task (*St*) when the derived belief on reader's experience is lesser or equal to threshold $d(A, El \leq Elt)$.
- Provides specific knowledge (*Sk*) when the derived belief on prior knowledge is at most equal to assigned threshold $d(A, Pk \leq Pkt)$ value.
- Advices on suitable materials *(Sm*) when the derived belief on task presentation is lesser than or equal to threshold $d(A, Tn \leq Tnt)$.

Prior to monitoring process, all the derived beliefs are measured as mentioned in Section 5.5.1. These derived beliefs are compared to its threshold values to determine its estimated level experienced by the readers. For example, the value of derived belief on prior knowledge is categorized into three levels (i.e., low, moderate, or high) based on its threshold *Pkt*. In this module, *Pkt* is assigned as 0.2, to represent the possible low level of reader's prior knowledge. Therefore, for any estimated value below this threshold value will trigger support mechanism related to improve prior knowledge level to solve the assigned task. Similarly, the experience level (*Elt)* and task presentation (*Tnt*) thresholds are assigned as 0.2 to activate related support mechanisms.

The computational implementation of this cognitive load support is described in Algorithm 5.6. In this case, support actions should be prioritized with respect to the derived belief. For example, the lowest derived belief will be given a higher priority in the support actions list compared to the highest ones (i.e., through the implementation of Bubble-Sort procedure). These processes also hold to support related cases in exhaustion and persistence. Based on this process, the agent will provide a particular support action from the list (support repertoire) and later amends its derived beliefs. If the obtained list is not empty (*length.List*≠ ∅), then the agent will prompt a confirmation message *s*(*A*, *Cdi*) to rectify the high experienced level of cognitive load level and later suggest a set of advices from the actions list ($List_i$) in sequential manners. Afterward, the related derived beliefs will be revised after the reader received the supports. This step is important to be evaluated in the next time interval as in *u*(*A*, *d*(*Tn*^*El*^*Pk*)). In case readers do not react for the first confirmation message, a second confirmation *s*(*A*, Cdi_{+1}) will be prompted to verify the experienced level of cognitive load and provide support actions. Without any appropriate feedback, no supports will be provided during this evaluation interval.

Algorithm 5.6: Cognitive Load Module

```
Input: d(A, Pk), d(A, El), d(A, Tn)
Output: To support cognitive load.
Start
   Initialization
      i←1
      Compute Priority // assuming Cl=1
         if d(A, Pk ≤Pkt)
              then Sk← Cl.Pk
                   List_i ← Sk
                   i←i+1
         if d(A, El ≤Elt)
              then St← Cl .El
                   List_i ← St
                   i←i+1
         if d(A, Tn ≤Tnt)
              then Sm← Cl .Tn
                   List_i ← Sm
                   i←i+1
         Bubble sort (List) // ascending
         if (length.List≠ (∅))
              then s(A, Cdi)
                   if (Cdi)
                        then for i← 1 to length.list
                                  do g(A, List_i)
                                  u(A, d(Tn^El^Pk))
                   else s(A, Cdi+1)
                        if (Cdi+1)
                             then for i← 1 to length.list
                                       do g(A, List_i)
                                       u(A, d(Tn^El^Pk))
         else g(A, Sm^St^Sk)
              u(A, d(Tn^El^Pk))
End
```


Moreover, the agent may suggest all support actions in parallel when the reader is experiencing an intense cognitive load level (i.e., when consistent checking *g*(*A*, *Sm^St^Sk*) is being triggered). Also, the steps in algorithm 5.6 are visualized in Appendix D. All of the previous algorithms were developed to permit an ambient agent with reasoning abilities in predicting reader's conditions. This is crucial in providing a proper intervention to help readers while performing reading tasks. Moreover, these processes will be autonomously executed unless an external interruption stops the reader from performing the process as depicted in Figure 5.9.

5.7 Results for the Ambient Agent Model Integration

In order to utilize the ability of an ambient agent model in a real-world, a set of integration algorithms was developed (as in Section 5.6). These algorithms are essential to ensure the correctness of support actions with respect to the domain model. Therefore, this section discusses how the ambient agent model could be devised by shedding further lights related to the monitoring and assessment components for related scenarios with respect to the persistence of readers when they are handling difficult reading materials. Figure 5.15 visualizes the monitoring mechanism related to persistence level. In this case, it provides basic description in monitoring persistence level (*Pr*) and providing support actions such as praising (*Ps*) and motivational talk (*Mt*). Similarly, a praising cue to maintain reader's good progress (*Pm*) will be triggered if the persistence level is at least equal to the assigned activation threshold ($dRp/dt > 0$ and $Rp >= Rpt$). Correspondingly, a continuous and monotonic decreasing level in persistence [$a(A, dPr/dt \leq 0) \wedge a(A, Pr \leq Prt)$] triggers a motivational talk (*Mt*) mode.

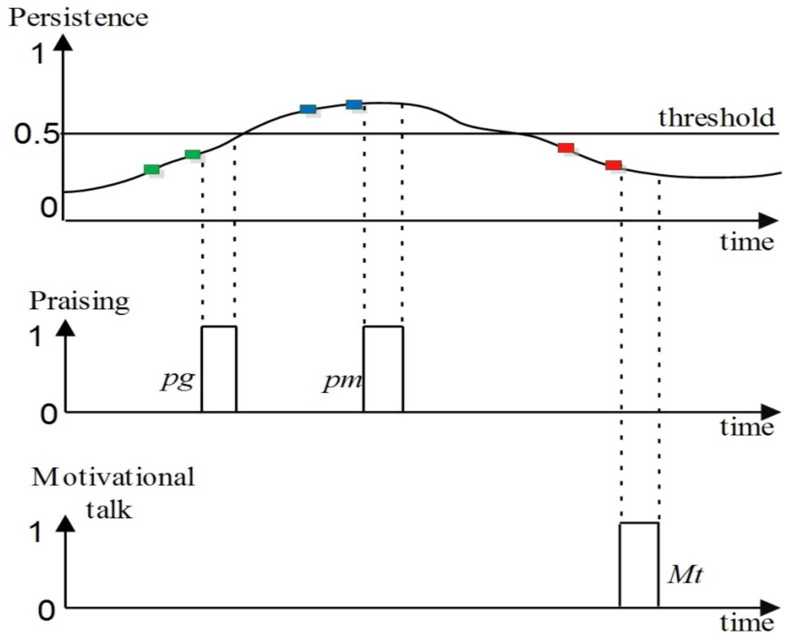

Figure 5.15. Persistence Support within the Ambient Agent

From the previous explanations, a set of simulation traces that describe selected scenarios related to the developed integrated algorithms (i.e., using LEADSTO platform) are generated. Figure 5.16 summarizes the simulation results of the implementation for these integration algorithms.

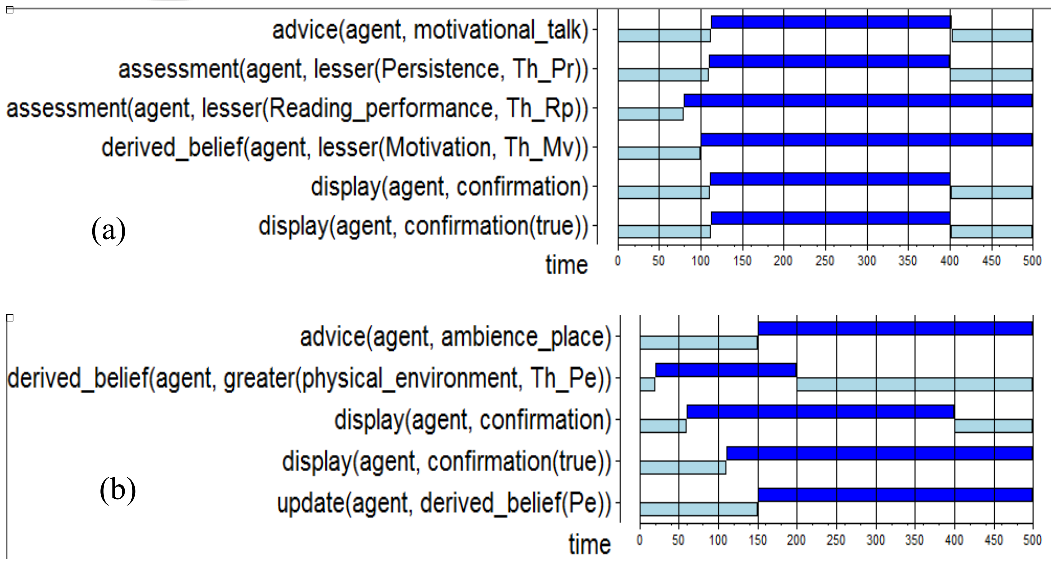

Figure 5.16. Simulation Results of an (a) Environment Evaluation, and (b) Motivational Talk

Figure 5.16(a) summarizes the simulation traces pertinent to Algorithm 5.4 (i.e., persistence module as in Section 5.6.5). It shows that when the agent evaluates the reading performance and persistence levels are low and it believes a reader's motivation level is below the threshold, then a confirmation screen will be prompted to provide a motivational talk. The complete description for these processes is presented in Section 5.6.5. Correspondingly, Figure 5.16 (b) visualizes the simulation traces related to Algorithm 5.1 (i.e., environment evaluation module as in Section 5.6.2). The process describes that when the agent believes a reading environment is non-conducive for reading purposes, then the agent prompts a confirmation screen to confirm its belief. For example, if its belief holds *true*, then the agent provides a piece of advice to ensure the reading room is more comfortable for reading purposes.

5.8 Preliminary Findings for a Reading and Robot Design Survey

Prior to the beginning of this study, a pilot study was conducted to get profound insights on the design perspectives of the robot, and primarily implemented to select the most preferred object to be represented as a reading companion robot. It is essential to determine the qualities that a reader prefers to be incorporated into the robot design such as preferences of having a companion robot. The following Sections 5.8.1 and 5.8.2 provide detailed explanations for the pilot study.

5.8.1 Survey Methodology

First, a set of questionnaires for survey purposes was designed and disseminated to get descriptive analysis on various issues related to the design of a companion robot. This questionnaire was developed based on 7-point Likert-scale (*1-Strongly Disagree, 2-Disagree, 3-Slightly Disagree, 4-Neutral, 5-Slightly Agree, 6-Agree and 7-Strongly*

Agree), multiple choices, and priority questions. Furthermore, the personality of respondents was captured through an adopted survey as used in John and Srivastava (1999). The complete questionnaire can be found in Appendix F.

Later, these questionnaire forms were disseminated to 100 both undergraduate and postgraduate students at Universiti Utara Malaysia with 91 forms were returned. Additionally, all respondents received a token as a gift. Since most of the respondents were not familiar with robotics technology, a comprehensive detail about a companion robot was provided together with the survey. The respondents' confidentiality was intact by not capturing their personal information.

The instruments of this questionnaire were evaluated to ensure its reliability and validity. The reliability analysis was based on the Cronbach's Alpha value, which is the representation of a lower level of internal consistency with its supposition of parallel measures. Based on StataCorp (2013), a value of $\alpha \geq 0.7$ could be considered as a significant value that ensures the instruments to be considered as reliable. The results from this analysis are presented in Table 5.4.

Table 5.4

Reliability Analysis

Variable	Number of Item	Cronbach's alpha
Preferences in robot	4	0.832
Challenges in reading	3	0.785

Similarly, the factor analysis was conducted to evaluate the capabilities of the instrument to measure the actual (expected) constructs. This evaluation has also been conducted through the analysis at loadings of each variable as depicted in Table 5.5. The extraction sums of squared loading values represent the variance between the factors that measure a particular variable where the highest variance is the strongest correlation between the factors.

Table 5.5

Factor Analysis Measurement

	Extraction Sums of Squared Loadings		
Variable	**Total**	**Variance (%)**	**Cumulative (%)**
Challenges in reading	2.108	70.257	70.257
Preferences in robot	2.656	66.400	66.400

It is important to mention any constructs that scored above 60 percent can be considered as valid for the measurement (Hair, Black, Babin, & Anderson, 2010).

5.8.2 Survey Results

The collected data from 44 male and 47 female students were statistically analysed using statistical analysis package (SPSS version 21) and spreadsheets (Microsoft Excel 2010). Appendix G summarizes additional information about the demographic of the respondents. Generally, the study was conducted into two folds; 1) challenges in reading and 2) favourable design qualities of the robot. For the first fold, most of the respondents have shown that they encountered challenges in reading and potentially hampered their performances with the scores of Mean= 5.08, and Standard Deviation=1.231. Table 5.6 summarizes the results of the main challenges readers have encountered during reading.

Table 5.6

Challenges in Reading Items

Items	Mean	Std. Deviation
It's easy for me to get distracted/ lose concentration during reading process	4.44	1.522
Reading for a very long duration causes me fatigue such as eye strain and backache	5.47	1.377
Reading for a very long duration causes me mental exhaustion such as lack of focus and tiredness	5.34	1.515

From Table 5.6, it shows that fatigue, mental exhaustion and distraction are among the main challenges encountered by readers. In addition, the results for robot's preferences in assisting readers was promising (*mean*=4.79, *std. deviation* =1.166). Table 5.7 summarizes the details of information for item preferences within the robot. Another interesting finding revealed that readers prefer to have a companion robot assisting them during reading task regardless their personality. This finding has also confirmed there is no significant correlation between personality and preferences in robot. Thus, those aforementioned results provide an evident and proper motivation why a reading companion robot is needed.

Table 5.7

Preferences in Robot Items

Items	Mean	Std. Deviation
I like the idea of having a personal robot that can support my reading process	5.10	1.484
Personal robot can encourage/motivate me during reading	4.51	1.493
Personal robot can help me to reduce my fatigue such as backache and eye strain during reading	4.82	1.371
Personal robot can help me to reduce my mental exhaustion such lack of focus and tiredness during reading	4.77	1.367

From Table 5.6 and 5.7, it can be concluded that respondents encounter some challenges while performing reading with specific tasks and prefer a companion robot to accompany and assist them. In addition, respondents were asked about their perception of having a companion robot and they responded positively towards that idea. Figure 5.17 visualizes respondent's image towards having a companion robot.

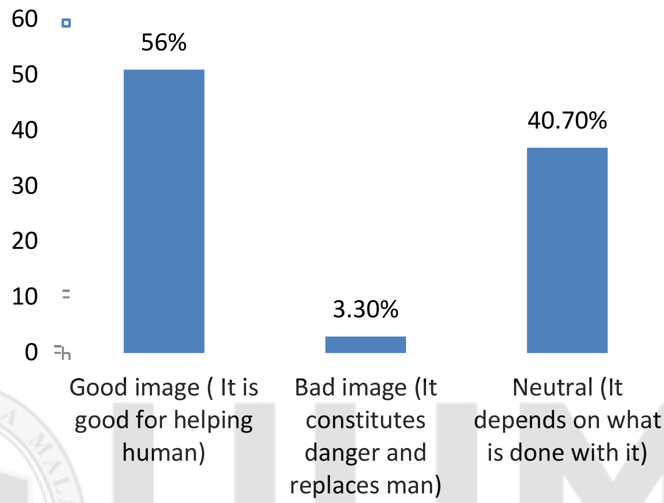

Figure 5.17. Results for Images of Having a Personal Robot

From this survey, the first conclusion can be derived regarding the object to be represented as a personalized medium for a reading companion robot. The results have shown that respondents are generally in favour for a table lamp object to be represented than other objects (*mean* 4.26 and *std. deviation* 0.828). Figure 5.18 shows the objects' priority to be chosen as a reading companion robot.

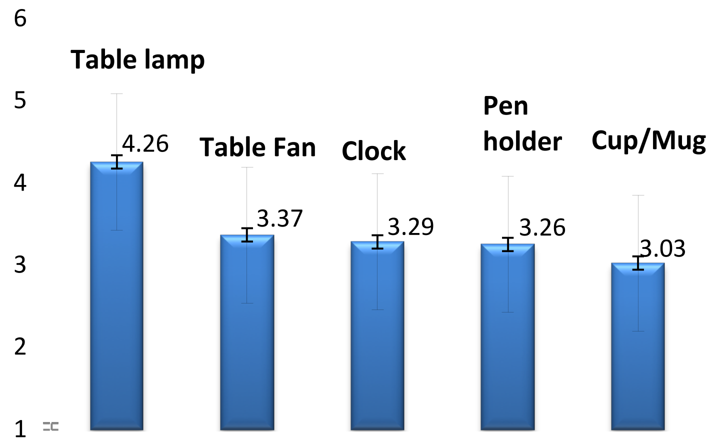

Figure 5.18. Five Objects Related to the Representation of a Companion Robot

Similarly, the embodiment aspect of a companion robot is also evaluated in this study where a physical embodiment received the highest preference as 45 percent (41 respondents) of respondents prefer a companion robot to be designed as a physical entity.

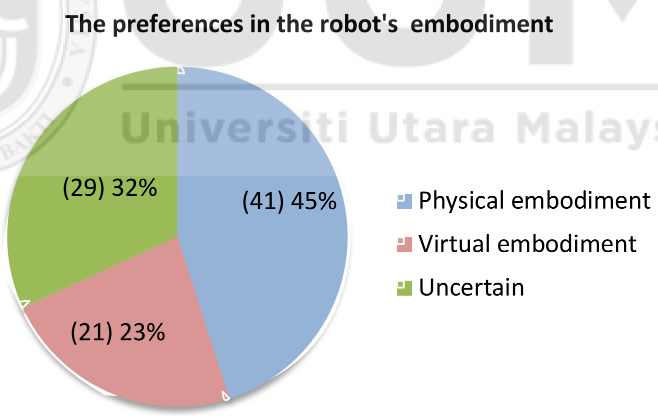

Figure 5.19. Embodiments in Companion Robot

Contrarily, a virtual embodiment of a companion robot received only 23 percent (21 respondents) preferences from the respondents and the remaining 29 percent (32 respondents) of respondents were uncertain about their preferences. Figure 5.19 summarizes respondents' preferences related to the design of a companion robot. Several other interesting issues were also explored to understand respondents' preferences related to the design of a companion reading robot. The detailed results were shown in Appendix G.

5.9 The Overall Design of the Companion Robot

From the results presented in previous section, the table lamp object has been selected as the most preferred choice and therefore is used as a physical medium for a companion robot. This robot is equipped with the reasoning engine based on the integrated ambient agent model (as described in Section 5.6). Figure 5.20 illustrates the overall idea of using an ambient agent model (software agent) as the reasoning engine for the companion robot.

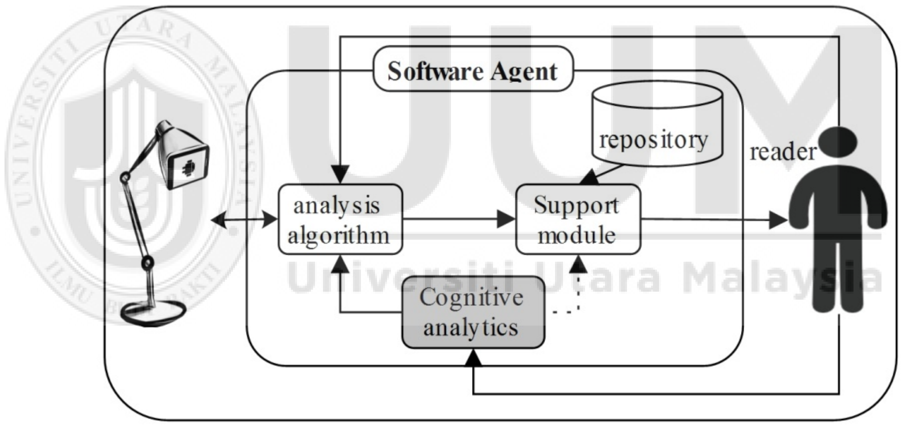

Figure 5.20. The Integration Between Software Agent Modules and a Table Lamp Robotic Medium / Object

First, the software agent evaluates reader's conditions (by utilizing an analysis algorithm as mentioned in Section 5.6). The result of this evaluation is based on observations and the developed reader's cognitive model of cognitive load and reading performance (cognitive analytics). Once the undesired condition or effect is detected, then related support actions will be selected from the support actions repository to curtail the undesired effect. In addition, this chapter delineates the hardware and software design components of the proposed reading companion robot or IQRA as depicted in Figure 5.1.

Based on Figure 5.1, the robot software design consists of (1) *Robot-Interface* to observe readers condition, display supportive actions, and show social animated interface, and (2) *Physical-Social-Gesture* to represent the robotic social cues and its movement. These components will be explained throughout next sections. The reading companion robot (IQRA') used an Android-based smartphone that runs all computational units and regulates all microcontroller and servo-motors components. Figure 5.21 shows the initial idea of the robotic platform in action.

Figure 5.21. Initial Conception of a Table Lamp-Inspired Robot

Generally, Figure 5.21 visualizes how the proposed reading companion robot will be positioned on a table where the ideal distance is specified. The details of hardware and software components of the robot and how they have been designed and integrated will be covered in Section 5.9.1 and 5.9.2.

5.9.1 Hardware Design

Once all robotic components were designed, several design iterations were involved to obtain the final robot outlook. First, a paper design was used to visualize the hardware design and it serves as a guideline about the appearances of the table lamp inspired robot. The early robot design is presented in Figure 5.22.

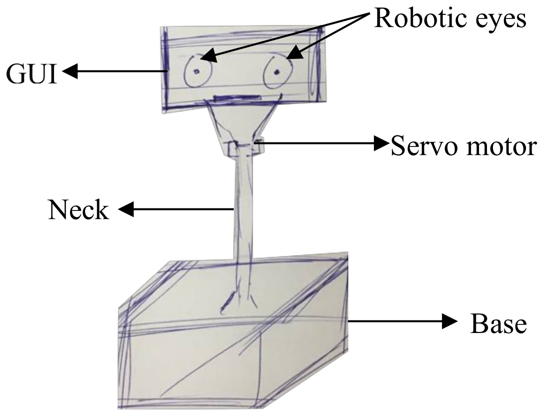

Figure 5.22. First Iteration of the Robot Design

In a step later, more details descriptions were considered to specify the real hardware components such as motors' positions to regulate the entire movement of the robotic platform. Also, the possible degree-of-freedom (DOF) angles were considered during this stage. This second iteration design includes different hardware components such as an Android phone, a DC motor to control the movement of the robot's arms, and a servo motor to manage social interaction by using the robot's head.

Moreover, a box-like base (located at the bottom of the robotic arm) to hold all hardware components and cover the electronic apparatus such as a power supply has been integration in this stage. The results from the second iteration of the robot design are presented in Figure 5.23.

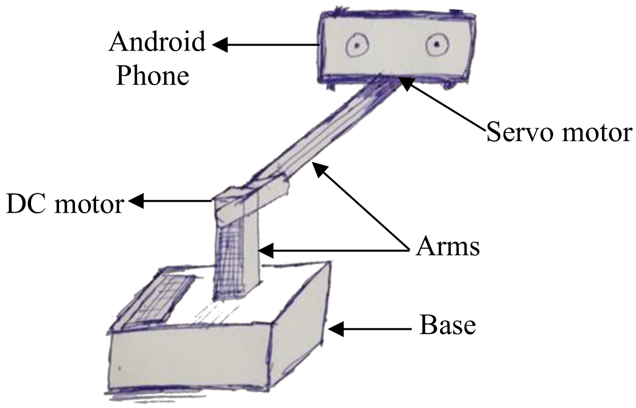

Figure 5.23. Results of the Robot Design in Second Iteration

Finally, the third iteration was conducted to include the details of possible robotic platform development such as the integration of Raspberry Pi motors controller and drivers, and hollow-neck and arm placement. Figure 5.24 shows the final paper prototyping stage prior to the solid modelling stage.

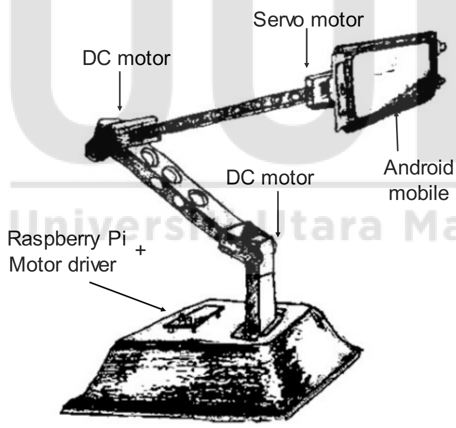

Figure 5.24. *Final Robot Design Prior to the Solid Modelling*

Once the paper prototyping stage has been finalized, the hardware architecture with all internal components' specifications were designed (as depicted in Figure 5.24). The specified electronic components were chosen based on special criteria to form a table lamp-like robot. These inter-connected components are depicted in Figure 5.25.

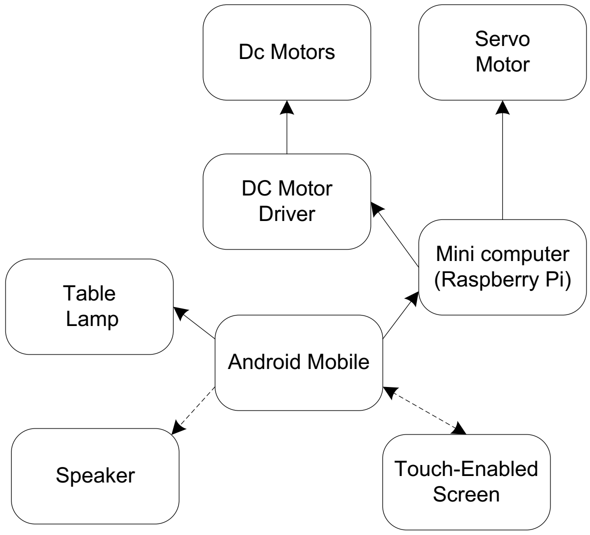

Figure 5.25. A Diagram of Hardware Components in the Robot

From Figure 5.25, the inter-connected components are; (1) *human-robot interface* by using an Android mobile Platform, (2) *microcontrollers* (Raspberry Pi and motors' driver) to control the robotic mechanical body, (3) a *table lamp* like body as a robotic physical base, and (4) a *servo* and two *DC motors* to facilitate robot's arm and neck movements. The details of these components and its electronic circuit design were discussed in Appendix H.

5.9.2 Software Design

As IQRA' requires an integrated component between robotic design and ambient agent model, any software design should consider the details of this integration process. For this, defined concepts from Section 5.6 were used to integrate the developed model into the robot. For example, when the robot observes there are some levels of sound in the room, then it will compute the basic belief about that particular noise level.

$$observation(robot, sound(level)) \twoheadrightarrow basic\_belief(robot, noise(level))$$

Likewise, related additional procedures were generated to control both mechanical body and animated user interface of the robot. To achieve this, different pieces of software were developed for specific assigned tasks. These pieces of software are; (1) a *main controller* to coordinate all input and output (I/O) and handle the overall human-robot interaction, (2) a *motor control system* to coordinate and control the mechanical body, and (3) software to control the *animated face* of the robot.

Control System Architecture

The main system serves as a controller to handle the flow for both interaction and communication channels between all subsystems. This control system is coded in Java programming language and communicated with other subsystems using Java classes or Sockets (controlling all motors). The overall high-level software architecture that described software components is depicted in Figure 6.26. On top of the *Main Control System* Java class, three are three different classes were developed, namely; (1) user interface class (user input, screen display, animated robot face), (2) off-the-shelf Android text-to-speech (TTS) class to convert texts into speech, and (3) the Raspberry Pi microcontroller class (written in Python programming language) to handle main software communication over Sockets programming. A *socket* is a communications connection point (endpoint) that developer can name and address in a network. Socket programming provides Socket Application Programming Interfaces (APIs) to establish communication links between remote and local processes (as it is a network standard for TCP/IP).

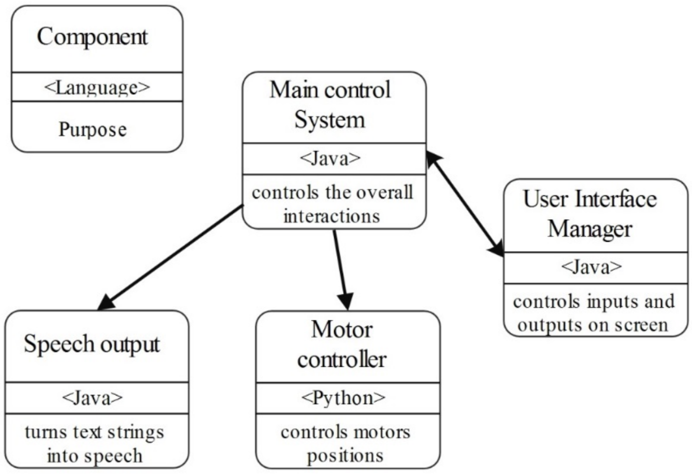

Figure 6.26. High-level Software Architecture

The implemented software architecture forms a robot's communication pipeline as depicted in Figure 5.27. This diagram represents an internal system architecture, which was fully implemented on an Android-based smartphone. Also, the diagram provides comprehensive details about the information flows between the different classes for the robotic application.

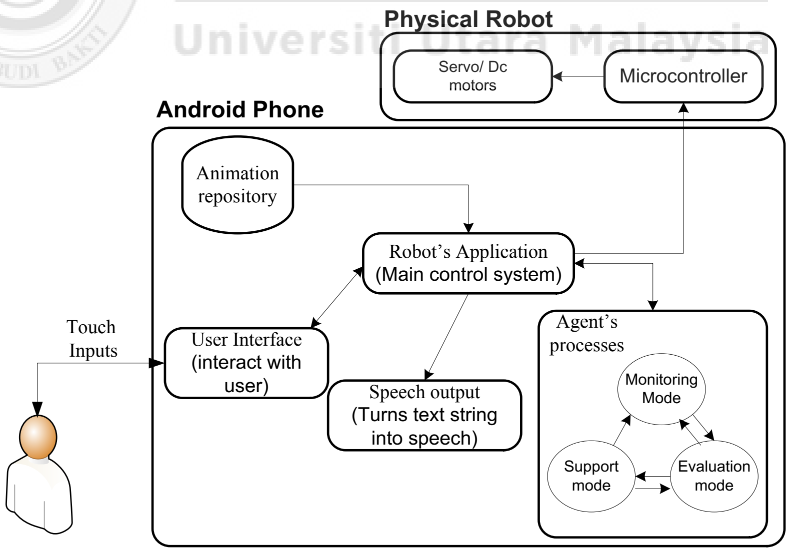

Figure 5.27. Robot's Communication Pipeline (Internal Software Architecture)

From Figure 5.27, the following functionalities of the robot application are designed and developed.

Main Control System: as a part of its core functionality to execute the ambient agent model. This function integrates all different classes such as animation, and motor controller classes in seamless manners.

Animated Face: one of the essential software components is to play a series of animations and generate a believable robotic interface. During the monitoring period, the robot retrieves related animations from repository and plays them on the robotic Android smartphone screen.

Motors Controller: a communication between the phone and robotic physical body. The Main Control System transmits the motors positions to the Raspberry Pi microcontroller system over Socket. Later, the motor system on a Raspberry Pi (using Python class) controls the motors movement.

User Interface: apart from displaying an animated face, a customized touch- enabled interface is designed to get inputs from user and show spoken texts on the smart phone screen. Also, it has been customized to display a set of learning materials and play related videos as well.

5.9.3 Human-Robot Interface

Generally, the main goal of designing interactive user input interfaces is to minimize possible demands from the user while performing an assigned reading task. Moreover, in any robot-based platform, it has become indispensable to design an interface to promote social interaction and believable behaviours (Kidd & Breazeal, 2008). It means robot's interfaces must offer believable social cues and communicate to the user in social manners (either via verbal or non-verbal cues). Furthermore, the interface must support the ability to allow feedbacks in a non-linear fashion. Contrary to the linear approach, the non-linear feedback reduces the predictable patterns of interaction and later leads to a natural and believable interaction (Marti, Giusti, & Bacigalupo, 2008).

Having these design perspectives in mind, a series of design interactions has been accomplished to come out for the finalized user interface. For example, IQRA' requires four different basic types of screens, namely; (1) shows spoken outputs from the robot in leveraging the interaction and support the user, (2) gathers user inputs prior to start monitoring and getting user's feedback during the course of interaction, (3) displays the predefined time-frame animated face, and (4) plays related videos as one of the support actions. For the first concept, the design perspective provides an alternative for users who are unable to understand the speech outputs due to some circumstances (difficulty to comprehend due to dialectic issues or Received Pronunciation (RP) factors) by showing the textual output version while performing interaction with users. Second, both textual input and slider bar approach are used as an information capturing mechanism to facilitate data entry. These human-robot interfaces were developed based on iterative prototyping methods (Walker, Takayama, & Landay, 2002) which include low and high fidelity prototypes. The prototyping results from low and high fidelity prototypes were presented in Appendix I.

Robot User Interface

This stage begins after all Lo-Fi and Hi-Fi prototyping processes have been completed. The Android programming language was selected as a programming platform to control all robotic computational properties and human-robot interaction. For example, Figure 5.28 shows the login interface for IQRA'. This login interface performs a user authentication process for a legit authorized access.

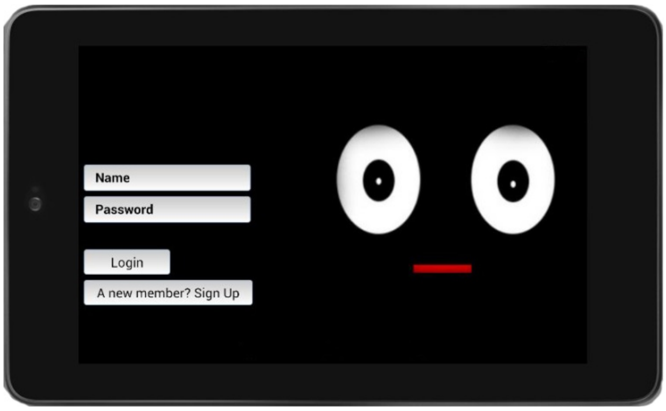

Figure 5.28. Robot Login Interface

Another example is shown in Figure 5.29 where this user interface is developed to observe reading task materials. Towards this end, the robot observes how reading task has been presented to establish the derived belief about that particular event. For example, two questions (based on a 7-Likert scale) were prompted using a slider-based input medium to collect information from users. The slider-based input allows a numerical value ranges between 0 and 100 for basic and derived beliefs computational purposes.

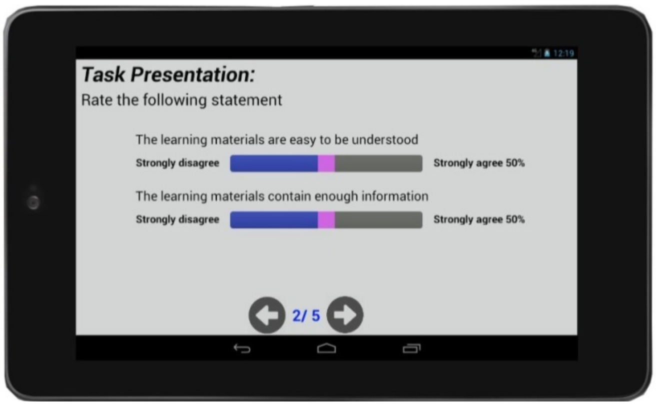

Figure 5.29. Robot's Observation Interface

For example, from this input (belief about task presentation), the derived belief is computed using the following equation:

$$derive\_belief(robot, task\_presentation = \alpha.\frac{Q1}{100} + (1-\alpha).\frac{Q2}{100})$$

This equation provides a normalization score ranging from 0 to 1 based on a regulated parameter (α). Later, related questions about the task presentation were aggregated to generate a basic belief about the task presentation. Similarly, this concept has been used to measure robot's observations based on basic and derived beliefs prior to any monitoring process. Another example (Figure 5.30) shows the provided support for a motivational talk. For this, selected phrases will be chosen to improve reader's motivation to stay and continue a reading task.

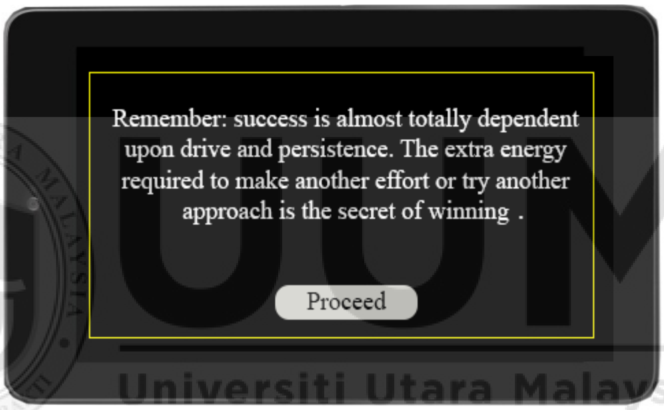

Figure 5.30. A Screen Showing a Motivational Text Printed to Screen

For more details, Appendix J provides different screenshots of user interfaces ranging from input capturing processes to the user feedback interfaces.

Social Module

Social Module is one of the important components to maintain proper relationships (e.g. short-term relationship) between readers and IQRA'. The combination of graphic editing tool (Adobe Photoshop) and Android programming (Java) was used to design and generate an anthropomorphic, sociable, and believable robot face. Figure 5.31 depicts some examples of the animated face including idle mode (a), eyes movements (b, and d), and blinking (c).

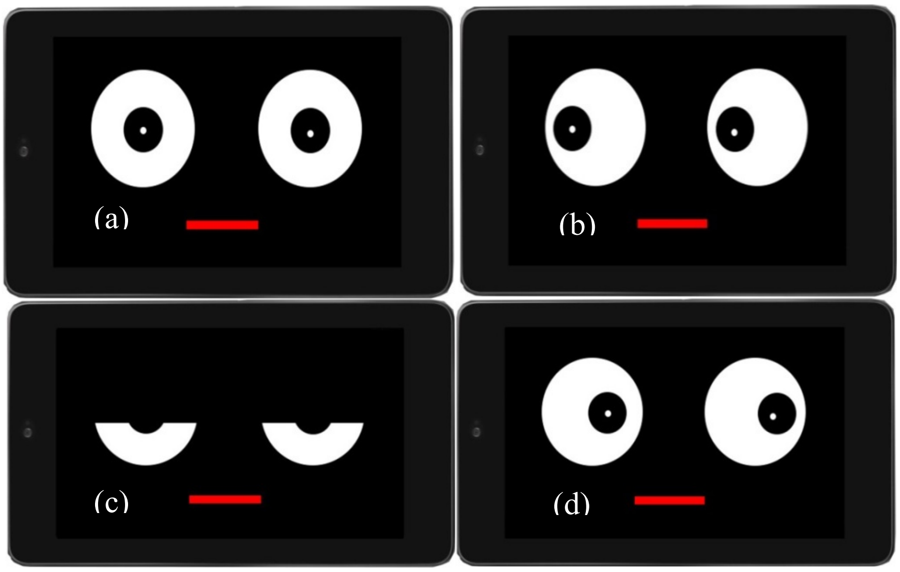

Figure 5.31. An Anthropomorphic Social Interface Design

The anthropomorphic animated face is executed during a monitoring process within a pre-defined time frame to serve two types of social-like movements. First, this animated face aims to regulate eye orientation from left to right (in parallel to the movement of robotic head). Second, it aims to perform eyes blinking as identical to the human blinking style. These social interface animated faces are designed to ensure IQRA' is capable in providing subtle interactions and advices to support readers. As such, IQRA' produces a life-like movement akin to human social behaviours when interacting to each other. The eyes orientation movement algorithm is developed to support the implementation of social like movements as in Algorithm 5.7. During the monitoring mode, the robot (*R*) will synchronously perform the left/right eyes movement (*p*(*R*, *Em*)) within a certain time frame (*m* minutes). Moreover, from the human eyes blinking behaviours study, a normal human eye blinks at average rate within three to 25 times per minute (Carney & Hill, 1982).

Algorithm 5.7: Robot_Eyes_Movement_Module

```
Input: Monitoring condition.
Output: Perform movement.
Start
    Initialization
        x←2
        i←2
        y←0
    Repeat
       For every m, p(R, Em) where m ∈ tp
          if(tp/m=x-1)
             then
                p(R, Em)
                x ←x+1
       For every y, p(R, Eb) where y ∈ts
          if(y>=threshold ) // threshold ← 1
             then for i←1 to random_generator (1, 25)
                   p(R, Eb)
                y←0
        y ←y+ts
    Until robot is in support mode
End
```

IQRA' human-like blinking behaviour plays an important role to preserve natural and believable human-robot interaction (Lehmann, Roncone, Pattacini, & Metta, 2016). Thus, the robot animated face is coded to perform eye blinks (*Eb*) within a random interval between 1 and 25 times per minute (*p*(*R*, *Eb*)).

Physical Social Gesture

The motor control software for IQRA' is written in Java and Python programming languages. The Java class is developed to provide a Socket connection and send command movements from an Android phone to the Raspberry Pi microcontroller. The Python class is developed for the Raspberry Pi microcontroller to generate a set of random selections mechanism for all three motors. The following algorithm 5.8 explains a random selection process for those robotic motors.

Algorithm 5.8: Robot_Body_Movement_Module

Input: Robot's monitoring /analysing condition.
Output: Perform movement.
Start
  Initialization
  Repeat
   For every ***n*****,** ***p*****(*****R*****,** ***Bm*****) where** ***n*** **∈** ***tp***
    if($tp/n=i$-1)
     then d= generate_random_number((d, select-motor(M_1,M_2,M_3))
      if (d=1)
       then $a(R, m(M_1))$
      if (d=2)
       then $a(R, m(M_1,M_2))$
      if ($d= m_3$)
       then $a(R, m(M_1, M_2,M_3))$
      $i \leftarrow i+i$
  Until support mode=true
End

From this algorithm, a random number ($1 \leq d \leq 3$) is generated to select the number of motors (M_d) that later will be activated as the movement for the robot (i.e., body movement (*Bm*)). For example, if the generated random number is equal to 2 (d =2), then the robot will activate both motor #1 and #2 to move and return to their initial fixed position ($a(R, m(M1))$). For the sake of simplicity, Table 5.8 shows the interaction modes when the robot performs any body movement or communicates with users.

Table 5.8

Robot Interaction Conditions

Robot's Conditions	Interaction Modes	
	Conversation	Movement
Start up		X
User data input	X	
Monitoring/Analysing mode	X	X
Support mode	X	
Switch off		X

It is interesting to mention that the randomized robotic movements will stop from running (halt-mode) while the IQRA's support mode is activated.

5.10 Finalized Robot Design

This section demonstrates the functionality of the robot in real-world settings. For this purpose, extensive prototype testing experiments were conducted to ensure the robot operates in an appropriate manner. For example, an experiment was conducted to check the Socket connection between the Android phone and Raspberry Pi microcontroller. Another experiment was conducted to ensure correct synchronization between the robotic eyes and body movements. Also, the main application was tested using the Android Studio Environment emulator as a final step prior to the deployment into the real Android Phone. Figure 5.32 represents the final version of the robot mechanical body without a robotic head.

Figure 5.32. Mechanical Body of the Robot

The final version of IQRA' is about 40 cm tall and is designed to sit on a table or countertop (as shown in Figure 5.33).

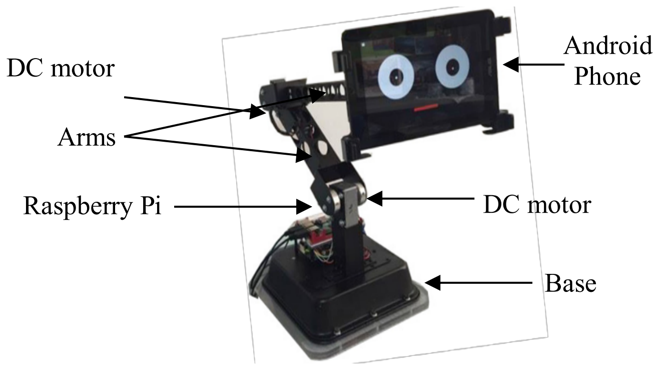

Figure 5.33. IQRA': The Reading Companion Robot

Based on this design, IQRA' has been used for the human experiment to check its reliability in monitoring and supporting readers during cognitively demanding reading tasks as discussed in Chapter Three. The results from this experiment are described in the next chapter (Chapter Six).

5.11 Summary

This chapter has pointed out the undertaken activities in developing an ambient agent model to support cognitive load during cognitively demanding reading tasks. The different models within the ambient intelligent agent architecture were conceptually designed (i.e., belief, analysis, and support models) and formalized using First-order Predicate Logic (FOPL). Moreover, the temporal specifications were obtained to generate an executable ambient agent model for simulation purposes. Different cases were simulated to demonstrate the behavioural patterns of the developed ambient agent model. The simulation results have exhibited realistic behavioural patterns with respect to the grounding theories and empirical literature used in this study. The developed ambient agent model and its simulation results have achieved objective two as mentioned in Chapter One.

Also, this chapter presented six integration algorithms, developed to improve reasoning engine capabilities within an ambient agent-based technology. Furthermore, it deals with the essential steps that were taken to design and develop IQRA', the proposed reading companion robot. As such, this chapter also detailed-up the robotic software and hardware components and design. The developed integration algorithms and robot design have attained objective three that was stated in Chapter One. The next chapter discusses the evaluation process of the developed ambient agent model and its integration on IQRA'.

CHAPTER SIX
EVALUATION

This chapter mainly focuses on the evaluation processes that were conducted in two parts, namely; verification and validation. Section 6.1 covers results from the verification process dedicated to recognise the underlying process of the developed models. It includes either a mathematical analysis approach for the cognitive agent model (Section 6.1.1), or an automated trace analysis for the cognitive agent and ambient agent models (in Section 6.1.2 and 6.1.3 respectively). Section 6.2 deals with the results from the validation process that has been conducted through human experiments to evaluate the reading companion robot. Finally, Section 6.3 summarizes this chapter.

6.1 Verification

Within an agent modelling and simulation domain, the reliability and theoretical grounding of agent's models are among of the main challenges to be addressed in ensuring the correctness of the developed models. Within this context, the correctness of the model is generally understood to the extent of the model implementation conforms to its formal specifications, and it is free from any design and development errors. Also, it can be defined as the process aids of ensuring that the conceptual description and the solution of the model are implemented correctly (Voogd, 2016). This process is implemented to improve important understanding of the system behaviour, improve computational models, estimate values of parameters, and evaluate (either local or global) system performance (Aziz et al., 2013).

In the light of the above, there are two approaches were implemented to evaluate the proposed models, namely; (1) mathematical analysis aims to evaluate the stability of the developed cognitive agent model, and (2) automated trace analysis to evaluate both cognitive agent and ambient agent models based on grounded concepts and empirical findings in the literature.

6.1.1 Mathematical Analysis of the Cognitive Agent Model

The possible equilibria points and convergence scenarios are analysed as a significant milestone in agent-based modelling and they are considered as the successful representations of the behaviour of the "real-world" dynamical system by a formalized model (Aziz, Shabli, & Ghanimi, 2017). Thus, the temporal behaviour of the model is determined by the formal specifications such as the differential equations in describing the local or global properties, and its respective parameters. In mathematical analysis, one important assumption should be made; all exogenous variables are having a constant value. Hence, to analyse the existence of equilibria, the available instantaneous and temporal equations are replaced with values for the model variables such that the derivatives or the difference between t and $t + \Delta t$ are all set as 0. For instance, a generic differential equation used to formalize the model is as follows.

$$Y(t+\Delta t)=Y(t)+ \beta.Y.\langle change\_expression \rangle.\Delta t$$

This differential equation can be re-written into:

$$dY(t)/dt= \beta.Y.\langle \text{change\_expression} \rangle$$

Next, the equilibrium points will be generated when all $dY(t)/dt$=0. Thus, assuming all parameters are nonzero, this leads to the following equations where an equilibrium state is characterized by:

$$Gd= \gamma_{Gd}.Me + (1-\gamma_{Gd}).Me.(1-Gr) \qquad (6.1)$$

$$Rd = \eta_{rd}.Tc + (1- \eta_{rd}).Sa \tag{6.2}$$

$$Sa = \lambda_{sa}. [w_{sa1} .Tp + w_{sa2} .Pe] + (1- \lambda_{sa}). [Tp. Pe. (1-Tn)] \tag{6.3}$$

$$Ev = \zeta_{ev}.(w_{ev1}.El + w_{ev2}.Pk) + (1- \zeta_{ev}) .Rn \tag{6.4}$$

$$\mathrm{Gr} = \omega_{gr}.\mathrm{Ev} + (1- \omega_{gr}).Ev.(1-Sa)) \tag{6.5}$$

$$Me = (1-Ma).Ml \tag{6.6}$$

$$Mv = \lambda_{mv}. Pp + (1-\lambda_{mv}).(1-Pe) \tag{6.7}$$

$$Ml = w_{ml1}.Id + w_{ml2}.Ed + w_{ml3}.Gd \tag{6.8}$$

$$Ma = w_{ma1}.Rf + w_{ma2}.Cp + w_{ma3}.Gr \tag{6.9}$$

$$Id = Rd.(1-Ev) \tag{6.10}$$

$$Ed = \beta_{ed}.Sa + (1- \beta_{ed}).Sa.(1-Gr) \tag{6.11}$$

$$Sh = \mu_{st.} Ce + (1-\mu_{st}).Ax \tag{6.12}$$

$$Ex = (w_{ex1}.Cl + w_{ex2}. Ce).(1-Rf) \tag{6.13}$$

$$Re = Pos ((w_{re1}.Cp + w_{re2}.Ev)-Me) \tag{6.14}$$

$$Rm = Pr.[1-(w_{rm1}.Ax + w_{rm2}.Cl)] \tag{6.15}$$

$$Ce = (\alpha_{ce}.Cl + (1- \alpha_{ce}).Ax)).(1-Re)) \tag{6.16}$$

$$Cp = \alpha_{cp}.Ev + (1- \alpha_{cp}).Pr. Ev.(1-Ae) \tag{6.17}$$

$$Rg = \zeta_{rg}.Ev + (1- \zeta_{rg}).[w_{rg1}.Rd + w_{rg2}.(1 -(Sa.(1-Ev)))] \tag{6.18}$$

$$Rf = \gamma_{rf}.(w_{rf}.Mv + w_{rf}.Rg) + (1- \gamma_{rf}).Re \tag{6.19}$$

$$\beta_{Ae}.(Sh-Ae).Ae.(1-Ae)=0 \tag{6.20}$$

$$\eta_{Ax}.Ex.(1-Ax)=0 \tag{6.21}$$

$$\beta_{Cl}.(Me-Cl).(1-Cl).Cl=0 \tag{6.22}$$

$$\eta_{Rp}.[((1-Me) .Rm)- Rp].(1-Rp).Rp=0 \tag{6.23}$$

$$\omega_{pr}.[[w_{pr1}.Mv + w_{pr2}.Rp]-Pr- \beta_{dp}].Pr.(1-Pr)=0 \tag{6.24}$$

Next, the equations with temporal specifications were identified. By assuming the adaptation rates ω_{pr}, β_{Ae}, η_{Ax}, β_{Cl}, η_{Rp} are equal to 1 and the decay rate β_{dp} is equal to zero, the following cases from Equations 6.20 to 6.24, can be distinguished:

$$(Sh - Ae). Ae.(1-Ae)=0$$

$$[[w_{pr1}.Mv + w_{pr2}.Rp]-Pr-\beta_{dp}].Pr.(1-Pr) =0$$

$$Ex.(1-Ax) =0$$

$$(Me - Cl).(1-\mathrm{Cl}).Cl=0$$

$$[((1-Me) .Rm)- Rp].(1-Rp).Rp=0$$

For the sake of simplicity, assuming $w_{pr1}.Mv+w_{pr2}.Rp= Aa$, and $(1-Me).Rm=Bb$, then, those cases can be represented as:

$$(Sh=Ae) \vee (Ae=1) \vee (Ae=0)$$
$$(Pr=1) \vee (Pr=0) \vee (Pr=Aa)$$
$$(Cl=Me) \vee (Cl=1) \vee (Cl=0)$$
$$(Rp=1) \vee (Rp=0) \vee (Rp=Bb)$$
$$(Ex=0) \vee (Ax=1)$$

Hence, a first conclusion can be obtained where the stability points can only occur when $Sh=Ae$ or $Ae=1$, or $Ae=0$ (as in Equation (6.20)). Thus, by combining these three conditions therefore a new set of relationships based on a conjunctive rule $(A \vee B \vee C) \wedge (D \vee E \vee F)$ expression can be formed:

$$((Ae=Sh) \vee (Ae=1) \vee (Ae=0)) \wedge$$
$$((Pr=1) \vee (Pr=0) \vee (\mathrm{Pr}=Aa)) \wedge$$
$$((Cl=Me) \vee (Cl=1) \vee (Cl=0)) \wedge$$
$$((Rp=1) \vee (Rp=0) \vee (Pr=Bb)) \wedge$$
$$((Ex=0) \vee (Ax=1))$$

This expression can be elaborated using *Law of Distributivity* as $(A \wedge D) \vee (A \wedge E) \vee (A \wedge F) \vee, \ldots, \vee (C \wedge F)$ and this will result:

$$((Ae=Sh) \wedge (Pr=1) \wedge (Cl=Me) \wedge (Rp=1) \wedge (Ex=0)) \vee$$
$$((Ae=Sh) \wedge (Pr=0) \wedge (Cl=1) \wedge (Rp=0) \wedge (Ax=1)) \vee \ldots \vee$$
$$((Ae=0) \wedge (Pr=Aa)) \wedge (Cl=0) \wedge (Rp=Bb) \wedge (Ax=1)) \qquad (8.25)$$

Equation (6.25) later provides large number of possible equilibrium points to be further analysed (in this case, it is up to $(2(3^4))$ =162 possible equilibrium points). It is of interest to mention that some equilibrium cases are not existed in the real-world scenarios or even in the simulation traces to be analysed. Therefore, such cases will be eliminated as the mathematical analysis will not be possible to achieve. For example, this can be seen in the following case.

$$((Ae=0) \wedge (Aa=Pr)) \wedge (Cl=0) \wedge ((Rp=Bb)) \wedge (Ax=1))$$

This case shows two conditions occurred simultaneously and impossible to be the case in the real-world situation. From this, accumulative exhaustion is equal to zero (Ae=0) and in the same time the accumulative level of experienced exhaustion is equal to one (Ax=1). Thus, this condition was removed from the analysis part. Note here, due to the large number of possible combinations, it makes hard to provide a complete classification of equilibria. However, for some cases the analysis can be pursued further.

Case #1: $Cl=1 \wedge Rp=0 \wedge Ax=1 \wedge Pr=0 \wedge Ae=Sh$

In this case, from Equations (6.1) to (6.24), Equation (6.12) it follows that:

$$Sh = \mu_{st}.Ce + (1-\mu_{st})$$

Assuming μ_{st} =0.5 (to represent an equal contribution for both sides), this results: Sh=Ce which depicts the level of short term exhaustion (Sh) is always determined by the level of cognitive exhaustion (Ce). In other words, the level of short term exhaustion is always high when the level of cognitive exhaustion is high and vice versa. The visual representation of stability points for both short-term exhaustion and cognitive exhaustion levels can be seen in Figure 6.1(c).

Moreover, by Equation (6.13) it follows that:

$$Ex = (w_{ex1} + w_{ex2}.\ Ce).\ (1-Rf)$$

Assuming w_{ex1} and w_{ex2} are equal to 0.5, this leads to:

$$Ex = Ce.\ (1-Rf)$$

This explains that recovery effort is negatively contributed to the level of experienced exhaustion. It means a reader with a high recovery effort experiences less exhaustion as he or she generates extra efforts to cope with high exhaustion (Bosse et al., 2008).

In the same vein, an experienced exhaustion and cognitive exhaustion levels are positively correlated to the level of cognitive exhaustion. The simulation results of this analysis can be seen in Figure 6.1 (d).

Next, from Equation (6.15), it can be found that:

$$Rm=0$$

This condition depicts the level of reading engagement is equal to zero when the reader experiences a high level in cognitive load, accumulative experience exhaustion, and accumulative exhaustion. In addition to this, both persistence and reading performance levels are also low. These findings are consistent to the literature as in Schnotz et al., (2009) and Mills, Bosch, Graesser, & D'Mello, (2014). Figure 6.1(d) shows the stable state condition for the aforementioned cases.

Moreover, by Equation (6.16) it follows:

$$Ce= (\alpha_{ce}+ (1-\alpha_{ce})). (1-Re)$$

Assuming $\alpha_{ce}=0.5$, this equivalent to:

$$Ce=1-Re$$

This equilibria point explains that cognitive exhaustion is negatively correlated to recovery effort. It means the level of cognitive exhaustion is high when recovery effort level is low and vice versa. The result can be visualized in Figure 6(c) and (d).

Finally, by Equation (6.17), it follows that:

$$Cp= \alpha_{cp}.Ev$$

Assuming $\alpha_{cp}=0.5$ then,

$$Cp=Ev$$

This condition explains the development of the critical point is highly depended to readers' expertise in tackling difficulty of the assigned task. Figure 6.1(c) depicts this condition.

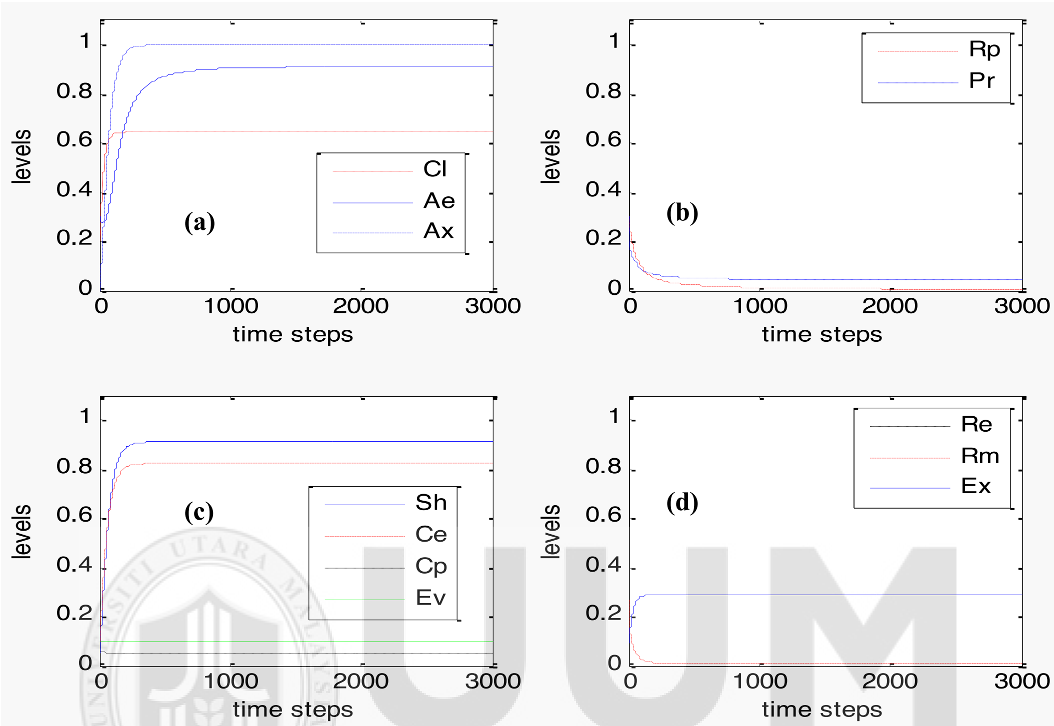

Figure 6.1. Simulation Results of Selected Stability Points

The same principle has been implemented in different cases and explained in the following cases.

Case #2: *Cl*=1

In this case, Equation (6.13) yields:

$$Ex=(w_{ex1}+ w_{ex2}.Ce).(1-Rf)$$

Assuming both of w_{ex1} and w_{ex2} are equal to 0.5. This will lead to:

$$Ex= Ce. (1-Rf)$$

Also, from Equation (6.15) it is equivalent to:

$$Rm=Pr. [1-(w_{rm1}.Ax+w_{rm2})]$$

This particular equilibrium proves that the formation of a reading engagement level depends upon the existence of prior persistence level. However, the high level of accumulative experienced exhaustion gives the opposite effect (Calderwood, Ackerman, & Conklin, 2014). The result of this condition can be seen as simulation traces in Figure 6.1.

In addition, by Equation (6.16) it follows:

$$Ce= (\alpha_{ce}+ (1-\alpha_{ce}).Ax). (1-Re)$$

Assuming α_{ce} equal to 0.5, this is equivalent to:

$$Ce=Ax. (1-Re)$$

This case provides a condition where the level of accumulative experienced exhaustion is positively related to the cognitive exhaustion. Also, it proves the evidence of physical tiredness increases the mental exhaustion level (Schaffner, Wagner, & Neckel, 2017). However, any high level of recovery effort gives an adverse impact towards this case.

Case #3: Ae=1 ∧ Ax=1

From Equation (6.13), the following case is equivalent to:

$$Sh=\mu_{st}.Ce+ (1-\mu_{st})$$

If the μ_{st} =0.5, this equals to:

$$Sh=Ce$$

This result is in line with the simulation traces as the short-term exhaustion increases when cognitive exhaustion level is reaching the maximum level (as shown in Figure 6.1(c)).

Moreover, by Equation (6.15), it follows:

$$Rm=Pr. [1-(w_{rm1}+w_{rm2}.Cl)]$$

Hence, both Equation 6.16 and 6.17 results:

$$Ce = (\alpha ce.Cl + (1-\alpha_{ce})).(1-Re)$$

$$Cp = \alpha_{cp}.Ev$$

This condition explains that the level of critical point is completely depends on expertise level. The simulation results prove this condition as depicted in Figure 6.1 (c).

Case #4: *Cl*=0 ∧ *Pr*=1

In this case, from Equation (6.15) it follows:

$$Rm = [1-(w_{rm1}.Ax)]$$

Assuming w_{rm1} nonzero, this is equivalent to:

$$Rm = 1-Ax$$

This condition explains the evidence of a negative correlation between reading engagement and accumulative experienced exhaustion. Also, it shows the high level of accumulative experienced exhaustion leads to the reading disengagement. In this case, these two possible conditions (Ax=1 ∨ Ax=0) explains existing negative correlation as follows. In the case of Ax=1, this leads to the following equation.

$$Rm = 0$$

However, in the case of Ax=0, this leads to the following equation.

$$Rm = 1$$

Furthermore, Equation (6.16) results:

$$Ce = ((1-\alpha_{ce}).Ax).(1-Re)$$

By Equation (6.17) it follows:

$$Cp = \alpha_{cp}.Ev + (1-\alpha_{cp}).Ev.(1-Ae)$$

Assuming $\alpha_{cp} \neq 1$ and $\alpha_{cp} > 0$, this is equivalent to:

$$Cp = Ev.(1+(1-Ae))$$

Finally, by Equation (6.13) it follows.

$$Ex = (w_{ex2} . Ce).(1-Rf)$$

Assuming w_{ex2} is nonzero, this leads to:

$$Ex = (Ce).(1-Rf)$$

Case #5: Cl=0 ∧ Ex=0

This case can be analysed by Equation (6.13), it is equivalent to:

$$(w_{ex2}.Ce). (1-Rf) =0$$

Assuming w_{ex2} nonzero, this is equivalent to:

$$Ce=0 \text{ and } Rf=1$$

In addition, from Equation (6.12) it follows:

$$Sh=\mu_{st}+ (1-\mu_{st}).Ax$$

Assuming $\mu_{st} \neq 1$ and $\mu_{st} > 0$, this is equivalent to:

$$Sh=Ax$$

Finally, from Equation (6.15), it follows:

$$Rm=Pr.[1-(w_{rm1}.Sh)]$$

If w_{rm1} is nonzero and $Sh \neq 1$, this leads to:

$$Pr = \frac{Rm}{1 - Sh}$$

In summary, the aforementioned cases provide the computational evidences of correctness of the cognitive agent model which depict the equilibria as obtained in the simulation traces discussed in Chapter Six.

6.1.2 Automated Analysis for Cognitive Agent Model

The Temporal Trace Language (TTL) is used to perform an automated verification of the specified properties and states against generated traces (Bosse et al., 2006). First, the model traces will be translated into LEADSTO traces. Later, these traces were verified using TTL. The overall transformation processes were visualized in Figure 6.2. Based on the concept discussed in Chapter Three, a number of dynamic properties from those traces were formulated using a sorted Predicate Logic approach to represent the model.

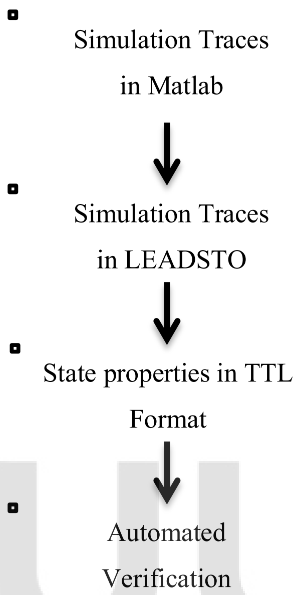

Figure 6.2. Steps to Use Matlab Traces for an Automated Analysis

There were five different properties were obtained from the literature to evaluate the internal validity of the model. These verified cases are as follows.

VP1: High Persistence Level Reduces Cognitive Load.

It is clear in the literature that readers with high persistence to continue the reading task tend to experience a low cognitive load level (Schnotz et al., 2009; Mills, Bosch, Graesser, & D'Mello, 2014).

$$
\begin{aligned}
&\textbf{VP1} \equiv \forall\gamma\text{:TRACE}, \forall t1,t2\text{:TIME}, \forall D,B1,B2, R1,R2\text{:REAL}, \forall X\text{:AGENT} \\
&[\text{state}(\gamma, t1) \models \text{persistence}(X, B1)\ \& \\
&\ \text{state}(\gamma, t2) \models \text{persistence}(X, B2)\ \& \\
&\ \text{state}(\gamma, t1) \models \text{cognitive\_load}(X,R1)\ \& \\
&\ \text{state}(\gamma, t2) \models \text{cognitive\_load}(X,R2)\ \& \\
&\ t2 > t1 + D\ \&\ B2 > 0.5\ \&\ B2 \geq B1] \Rightarrow R2 < R1
\end{aligned}
$$

The VP1 property is used to check the impact of reader's persistence on the level of cognitive load that readers experience during reading demanding tasks. It shows that readers with high level of persistence (e.g. with a value ≥ 0.5) experience low cognitive load at the next time step. Also, this property is consistent with the empirical findings obtained by Schnotz et al. (2009) and Millset et al. (2014) .

VP2: Prolonged Time Spent on Reading Leads to High Level of Exhaustion.

This selected property is used to evaluate the internal validity of the model as it shows a non-stop reading process later leads to the development of exhaustion. As a consequence, it will hamper the effectiveness of task-related performance (Treur, 2011). The implementation of this state property is as follows.

VP2 ≡ ∀γ:TRACE, ∀t1, t2:TIME, ∀M1, M2, D:REAL , ∀A:AGENT
[state(γ, t1)|= accumulated_exhaustion(A, M1) &
state(γ, t2)|= accumulated_exhaustion(A, M2) &
M1 ≥ 0.1 & t2= t1+D] ⇒ M2 ≥ M1

The property VP2 explains that the level of exhaustion increased throughout time (through the additional time steps and delay *D* factor).

VP3: Low Cognitive Load will Increase Reading Performance.

Readers with a low cognitive load level (especially for knowledgeable readers) tend to perform better in solving complex reading tasks.

VP3 ≡ ∀γ:TRACE, ∀t1,t2:TIME, ∀D,V1,V2, R1,R2:REAL, ∀X:AGENT
[state(γ, t1)|= cognitive_load(X, B1) &
state(γ, t2)|= cognitive_load(X, B2) &
state(γ, t1)|= reading_performance(X,R1) &
state(γ, t2)|= reading_performance(X,R2) &
t2 > t1 + D & B1 < 0.2 & B1 ≥ B2] ⇒ R2 >R1

This property used to check the impact of cognitive load on overall reading performance. For example, in this evaluation, the low level of cognitive load (e.g., with a value < 0.2) will enable readers to perform better. This result is in line with the literature as in Kalyuga (2011c) and Nicholson & O'Hare(2014).

VP4: The High Level of Expertise is Related to High Critical Power.

The expertise level influences the ability to generate additional efforts in regulating cognitive load during demanding tasks. For example, the accomplished readers are able to put forward extra efforts (e.g., having a high critical point level) to solve particular demanding task (Hockey, 1997).

> **VP4** ≡ ∀γ:TRACE, ∀t1, t2:TIME, ∀X1, X2, C, D:REAL , ∀A:AGENT
> [state(γ, t1)|= expertise_level(A, C) &
> state(γ, t1)|= critical_power(A, M1) &
> state(γ, t2)|= critical_power(A, M2) &
> C≥ 0.8 & t2= t1+D] ⇒ M2 ≥ M1

Also, this scenario has been observed by Treur (2011) within human's capacity, efforts, and task-related performances domains.

VP5: Non-Conducive Learning Environment Increases Cognitive Load.

This property aims to evaluate the effect of a non-conducive environment towards cognitive load. For example, in many literatures, by performing difficult tasks in uncomfortable or undesired environment lead to the deterioration of individuals' performance (Choi et al., 2014).

> **VP5** ≡ ∀γ:TRACE, ∀t1, t2:TIME, ∀V1, V2, Q, D:REAL, ∀A:AGENT
> [state(γ, t1)|= ambience_room(A, Q) &
> state(γ, t1)|= cognitive_load(A, V1) &
> state(γ, t2)|= cognitive_load(A, V2) &
> Q < 0.2 & t2= t1+D] ⇒ V2 ≥ V1

The property VP5 demonstrates that non-ambience place (e.g. as Q < 0.2 to represent a noisy room) will increase the level of cognitive load as time t_{n+1} progresses by *D* delay factor.

6.1.3 Automated Analysis of the Ambient Agent Model

The ambient agent model was evaluated via Temporal Trace Language (TTL). The flow of this process is depicted in Figure 6.3.

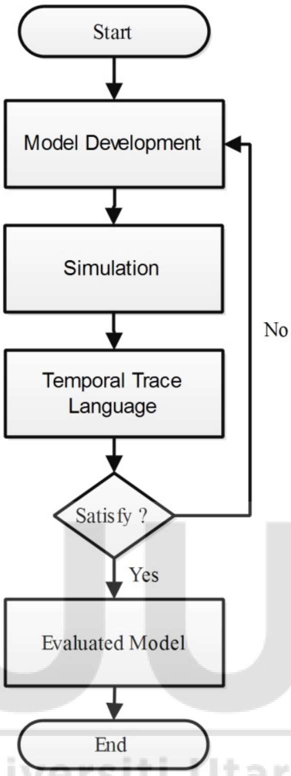

Figure 6.3. Ambient Agent Model Verification Process

For this purpose, five important properties were selected from the literature to evaluate the internal validity of the ambient agent model.

VPA1: Provide Social Dialogues when the Reading Performance is Low.

The ambient agent model assesses reader's condition as a basis to provide different kind of supports. This kind of support (e.g. social dialogues and motivational talks) is crucial as it provides positive feedbacks to elevate reader's persistence level (Noels, Clément, & Pelletier, 1999; D'Mello, Lehman, & Person, 2010; Brookhart, 2017).

VPA1 ≡ ∀γ:TRACE, t1, t2, t3:TIME, ∀M1, M2, D1, D2:REAL
[state (γ,t1) |= belief(robot, persistent_level(M1)) &
state (γ,t2) |= belief(robot, persistent_level(M2)) &
state (γ,t1) |= assessment(robot ,reading_peformance(D1) &
state (γ,t2) |= assessment(robot ,reading_peformance(D2)] &
t1 < t2 & M1 > M2 & D1 > D2] ⇒
∃t3:TIME > t2:TIME:[state(γ,t3) |=performed (robot, provide(social_dialogue)]

This property proves the ambient agent will provide social dialogues to readers when it believes that readers' persistence level is becoming low (M1 > M2) and reading performance is decreasing (D1 > D2) throughout time.

VPA2: Suggestion to Find an Ambience Place when Noise Level is High.

If the ambient agent predicts the room is not ambience for reading purposes (e.g., the noise level is high), then the ambient agent advices reader to ensure the room is suitable to execute the task. It is crucial as reading processes require a nice room with low potential disturbance to perform related tasks (Choi et al., 2014).

VPA2 ≡ ∀γ: TRACE, t1,t2, t3:TIME, N1, N2:REAL
[state(γ,t1) |= belief(robot, noise_level(N1)) &
state(γ,t2) |= belief(robot, noise_level(N2)) &
state(γ,t2) |= evaluation(robot, belief_ambience(no)) &
t1 < t2 & N1 > 0.6 & N1 ≤ N2] ⇒ ∃t3:TIME > t1:TIME:[state(γ,t3) |=performed (robot, advice(suggest_ambience_place))]

Therefore, by advising readers to ensure a proper reading environment for reading purposes is an essential element to increase reading persistence that later increases reading performance.

VPA3: Advice for a Short Break Session when the Exhaustion is Detected.

When the ambient agent evaluates readers are experiencing a high exhaustion level, then the ambient agent will provide a piece of advice for a short break.

$$
\begin{array}{l}
\textbf{VPA3} \equiv \forall\gamma\text{: TRACE, t1, t2, t3:TIME, E1, E2, d: REAL} \\
\text{[state }(\gamma\text{,t1}) \mid= \text{belief(robot, exhaustion\_level(E1)) \&} \\
\text{state }(\gamma\text{,t2}) \mid= \text{belief(robot, exhaustion\_level(E2)) \&} \\
\text{t1} < \text{t2+d\&E1} \geq 0.7\text{\&E1} \leq \text{E2]} \Rightarrow \\
\exists\text{t3:TIME} > \text{t1:TIME:[state(}\gamma\text{,t3)} \mid= \text{performed (robot, advice(short\_break))]}
\end{array}
$$

It is important for someone to get rest for a while as a high exhaustion level will deteriorate readers' performance (Henning, Jacques, Kissel, Sullivan, & Alteras-webb, 1997; Fritz, Ellis, Demsky, Lin, & Guros, 2013; Hunter & Wu, 2016; Kühnel, Zacher, de Bloom, & Bledow, 2017).

VPA4: Suggest Specific Knowledge when Cognitive Load is High.

If the ambient agent observes readers have not adequate knowledge in a particular subject matter and predicts a reader is experiencing a high cognitive load level, then the ambient agent suggests specific knowledge (i.e., providing hints).

$$
\begin{array}{l}
\textbf{VPA4} \equiv \forall\gamma\text{: TRACE, t1, t2, t3:TIME, Q1, Q2, d: REAL} \\
\text{[state }(\gamma\text{,t1}) \mid= \text{belief(robot, cognitive\_load(Q1)) \&} \\
\text{state }(\gamma\text{,t2}) \mid= \text{belief(robot, cognitive\_load (Q2)) \&} \\
\text{t1} < \text{t2: TIME+ d \& Q1} \geq 0.4 \text{ \& Q1} \leq \text{Q2]} \Rightarrow \\
\exists\text{t3:TIME} > \text{t1:TIME: [state(}\gamma\text{,t3)} \mid= \text{performed (robot, provide(hint))]}
\end{array}
$$

This TTL property evaluates simulation traces related to the provided support by an ambient agent for readers when it believes readers' cognitive load is becoming high (Koedinger & Aleven, 2007; Wu, Hwang, Su, & Huang, 2012; Leyzberg, Spaulding, & Scassellati, 2014).

VPA5: Provide Praising when Persistence is High.

If the ambient agent evaluates a reader's persistence level is high, then the ambient agent will praise the readers to encourage him/her in staying focus and continue reading.

$$\begin{aligned}&\textbf{VPA5} \equiv \forall\gamma\text{: TRACE, t1, t2, t3:TIME, V1, V2, d: REAL}\\&\text{[state } (\gamma,\text{t1}) \models \text{belief(robot, persistence\_level(V1)) \&}\\&\text{state } (\gamma,\text{t2}) \models \text{belief(robot, persistence\_level (V2)) \&}\\&\text{t1<t2: TIME+ d \& V1}\geq 0.7 \text{ \& V2}\geq\text{V2]} \Rightarrow\\&\exists\text{t3:TIME> t1:TIME: [state}(\gamma,\text{t3})\models \text{ performed (robot, action(praising-message))]}\end{aligned}$$

In many cases, praising plays an important role in increasing intrinsic motivation of individuals through a set of positive verbal feedbacks (Zentall & Morris, 2010; Mumm & Mutlu, 2011; Bear, Slaughter, Mantz, & Farley-Ripple, 2017)**.** It also has potential to increase the reader's motivation to perform the task.

6.2 Validation

This section presents the results from human experiment based on the implementation of IQRA' as a robot-based reading companion platform. In this experiment, 20 students were recruited from School of Computing, Universiti Utara Malaysia. This group of students consists of 16 males and four females. They were assigned into control (without robot) and experimental (with robot) groups. The details of this experiment protocols can be found in Section 3.7.2.2.

6.2.1 Pilot-test Study Results

Prior to the main experiments, a pre-test study was conducted for two reasons. First, it was implemented to understand the functionality of the developed reading companion robot. Also, it aims to investigate potential robot operational errors may occurs during the experiment. This part is important to obtain useful feedback to scrutinize the main experiment. Second, it provides a medium to test the experiment instruments (e.g. questionnaires) that essential to uncover any problems that may lead to biased answers.

As such, five students from School of Computing, Universiti Utara Malaysia were recruited for this purpose. The experiment protocol in selecting the respondents was based on a framework introduced by Bickmore et al. (2005) and has been presented in Chapter Three. The results for constructs in usability and functionality of the robot, have shown that all participants found IQRA' is interesting to interact with and easy to be operated. However, several suggestions for a number of robotic functionality were given. For example; (1) the voice of the robot during the interactions prompt and ambiguous, (2) the rapid and unnecessary movement of the robot was considered as 'disturbing', (3) the idyllic mode after playing videos was considered for interaction enhancement, and (4) the proximal distance between a robot and reader (e.g., the robot was slightly far from the users). These suggestions were considered to ensure more salient and subtle human-robot interaction. Thus, the robotic software components were re-programmed to meet those new requirements.

Also, as for the designed survey items all respondents understood the questions and managed to retrieve any information related to the questions. Moreover, the constructed sentences from the questionnaire did provide all necessary information required by the respondents.

6.2.2 Experimental Results

This section elaborates further discussions about the experimental protocol of the study results from the conducted experimental results. The experimental procedure to select respondents was observed to guarantee the homogeneity of the respondents. The homogeneity of the respondents is important to eliminate any possible factors that may lead to biased answers (as explained in Chapter Three). As explained before, there are two groups were involved, namely control and experiment. These respondents were asked to solve a task related to the Data Structure and Algorithm Analysis subject accompanied by using either tablet computing platform (later known as ***Tablet***) or robotic platform (***Robot***).

The underlying principle for this selection of two groups is to evaluate the integration of the ambient agent model into different mediums (tablet vs. robot) give different impact pertinent to the provided support. In addition, the experiment aims to investigate reader's attitude and perception towards using ***Robot*** and ***Tablet*** platforms. Figure 6.4 some physical settings during the experiment.

Figure 6.4. Respondents in the Physical settings

From Figure 6.4, the four physical conditions of using *Tablet* (6.4(a) and b) and *Robot* (6.14c and d) are shown while the respondents were trying to solve the Data Structure and Algorithm Analysis reading task (i.e., topics in Tower of Hanoi puzzle).

6.2.2.1 Respondent's Background

All respondents were selected based on the list of the students who obtained grades within the range from C- to C+ grade in their previous semester. This is important to ensure the basic knowledge for all respondents is within the same level in eliminating any selection bias. Moreover, the selected task needs more than an hour to be solved. A list of students was obtained and later an invitation to participate with a brief introduction about the experiment was sent via an e-mail. Figure 6.5 summarizes the overall respondents' selection protocol.

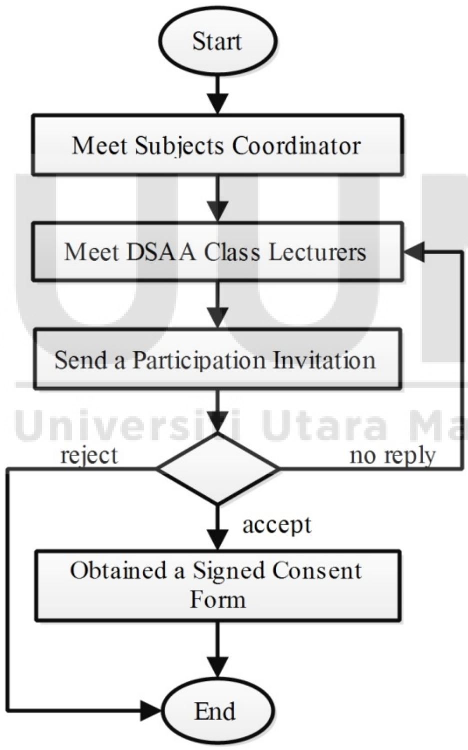

Figure 6.5. Flow Chart of Respondents' Recruitment

Prior to the experiment, a basic demographic questionnaire was distributed to get an insight about respondents (e.g., the entry level for respondents as shown in Figure 6.6). The age of all respondents is in a range between 19 to 30 years old.

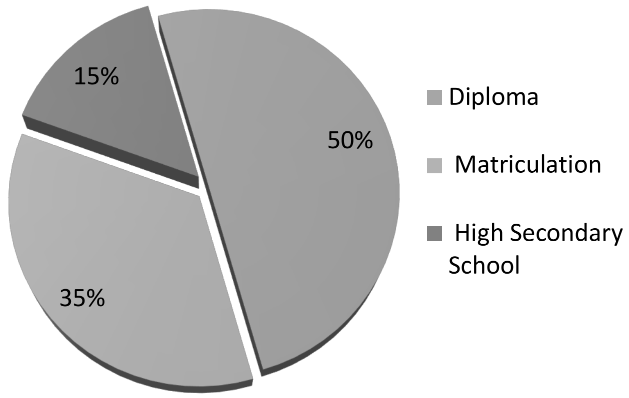

Figure 6.6. Respondents Educational Level

The selection of respondents also covers different nationalities where 60 percent of respondents are local Malaysian and the rest are foreign students (as shown in Figure 6.7).

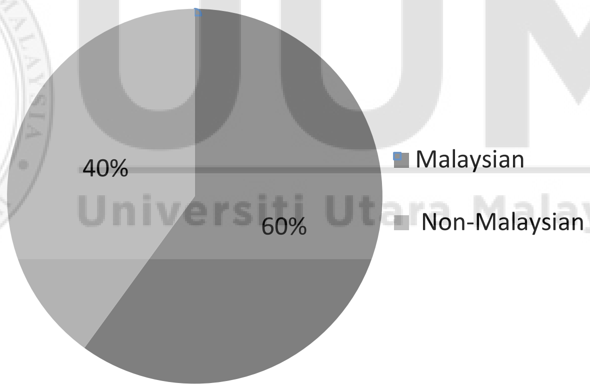

Figure 6.7. Respondents' Nationality

It is interesting to mention that these foreign respondents are coming from different countries such as Yemen, Bangladesh, Somalia, and Indonesia.

6.2.2.2 Cognitive Load Analysis Evaluation

This experiment is designed to evaluate the effects of the support based on an ambient agent model. During the experiment, respondents from both groups (*Tablet vs. Robot*) were prompted three times to rate the cognitive difficulty of the assigned task. The first question was prompted after the first 10 minutes and the rests for each consecutive 20 minutes. The results from the prompted question provide an insight about the overall difficulties of the assigned task. Thus, it provides a piece of information related to the successfulness of the support given by the ambient agent model.

During the first evaluation, both groups scored ‘high difficulty’ to solve the task with mean (M) and standard deviation (SD) values. These values are; (1) for control group (M=5.5, SD=0.85), and (2) for experiment group (M=5.3, and SD=0.823). However, for the second and third evaluation, both groups have reduced their cognitive difficulties level. In the second evaluation, for control group scored (M= 3.8, SD=1.135), whereas scores for the experimental group the values are; (M=4.2, SD=0.919). Towards the third evaluation, both groups indicated that the task was almost easy to be with scores for *Tablet* (M=2.8, SD=1.135) and *Robot* (M=2.7, SD=1.135). The complete result of the survey is depicted in Figure 6.8.

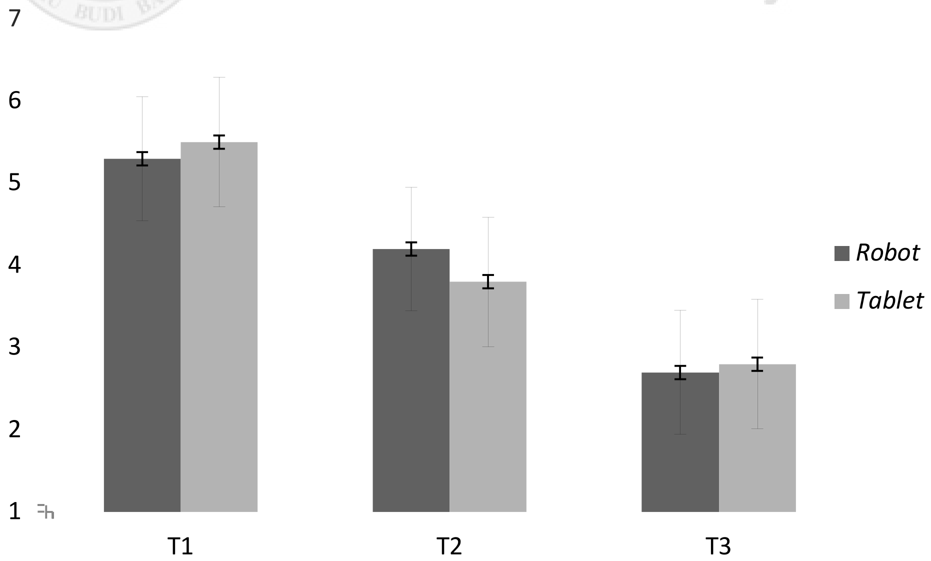

Figure 6.8. Results on Cognitive Load for Both Platforms

Apart from the descriptive analysis results that discussed above, further information in the form of inferential statistics is required to concretize the results and ensure the variances in mean values are not occurred by chance. For this reason, variance analysis of mean values for the two groups (*Tablet vs. Robot*) was conducted independently to conclude whether the difference in mean values is significant or not. The mean values for each group at the first (i.e., T1 in Figure 6.8) and third evaluations (i.e., T3 in Figure 6.8) were statistically analysed. In the case of *Tablet* group, a hypothesis was generated to ensure that the mean vale at the third evaluation (i.e., μ_{Tmean3}) is lower than the mean value at the first evaluation (i.e., μ_{Tmean3}). This shows the decrement in cognitive load negative impacts. The hypothesis formulation is as follows.

$$H1: \mu_{Tmean3} < \mu_{Tmean1}$$
$$H0: \mu_{Tmean3} \geq \mu_{Tmean1}$$

Also, a Paired-Sample T Test analysis (i.e., within participants) was performed to check whether it is possible to reject the null hypothesis (H0) and accept the alternative hypothesis (H1). The t test analysis results found that the difference between mean values is significant, t (9) =6.8, p<0.001. This means that null hypothesis was rejected.

Similarly, in the case of *Robot* group, a hypothesis was generated to check whether the difference in mean values between the first and third evaluation is significant or not. The formulation of this hypothesis is as follows.

$$H1: \mu_{Rmean3} < \mu_{Rmean1}$$
$$H0: \mu_{Rmean3} \geq \mu_{Rmean1}$$

The inferential statistical analysis (i.e., Paired-Sample *T* Test) found that the difference between the mean values is significant, t (9) =6.5, p<0.001. This result tells that the null hypothesis (H0) is possible to be rejected in favour of the alternative hypothesis (H1).

From the results mentioned above, the first conclusion based on descriptive analysis can be derived that the ambient agent model is capable to reduce the experienced cognitive load during reading demanding task. Furthermore, it is interesting to mention that at the end of the experiment, both groups scored a low cognitive load level with group *Robot* scored slightly better (with the differences up to 0.1). Also, the inferential statistical analysis showed that the difference between mean values for each group independently is significant. Based on the descriptive and t test analysis results, it has shown the integration of the ambient agent model is useful to reduce cognitive load during reading regardless platforms.

6.2.2.3 Perceptions about Reading Companion Robot

This section measures reader's attitude and perceptions towards a reading companion robot (in comparison to a *Tablet*) with homogeneous functionality (e.g. support providing process). To address this, six evaluation constructs are measured such as perceived likeability, perceived sociability, perceived intelligent, perceived usefulness, perceived social presence, and usability. These constructs aid to capture user's impression towards the reading companion robot. The descriptive and inferential statistics results are explained as follows.

Perceived Likability

Previous empirical studies have found that vocal and visual behaviours are essential indicators to measure user's impression towards robots (Bartneck et al., 2009). In this experiment, the likeability for both Robot and *Tablet* platforms as a reading companion artefact was measured based on 7-point semantic differential scale. The results have shown that the average of participants' ratings in response to likeability for both platforms are *Tablet* (M=3.92, SD=0.844) and *Robot* (M=5.74, SD=0.654).

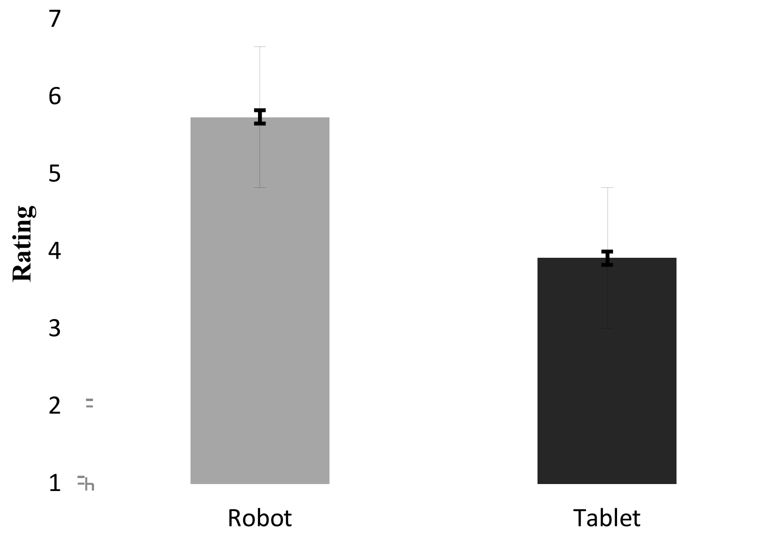

Figure 6.9. Likeability Ratings for *Robot* vs. *Tablet*

The inference analysis was performed to ensure the difference between the mean values presented in Figure 6.9 is significant. For this, a hypothesis was introduced and an independent *t*-test (i.e., between participants) was used for the analysis purpose. The formulated hypothesis is as follows.

H1: $\mu_{LRmean} > \mu_{LTmean}$

H0: $\mu_{LRmean} \leq \mu_{LTmean}$

The hypothesis H1 suggested that participants in *Robot* group significantly perceive the robotic platform more likeable over the tablet platform ($\mu_{LRmean} > \mu_{LTmean}$). This hypothesis was confirmed and the null hypothesis H0 was rejected as the independent t-test analysis results showed that the variance between mean values for both groups is significant, $t(18) = 5.3$, $p<0.001$. Both descriptive and *t*-test analysis results indicate respondent's perceived robotic platform (IQRA') as more likeable compared to the tablet platform. Although, both results on cognitive load evaluation (*Tablet* and *Robot*) were able to reduce the experienced load, respondents are in favour to have a physical robot as a reading companion (as shown in Figure 6.9).

Perceived Intelligence

In this construct, the ability of the reading companion robot to express human-like intelligence behaviours is measured. During the interaction, if users interpret robot's behaviours as natural and human-like manners, it provides an indicator of some level of robot's intelligence level (Bartneck et al., 2009). From the experiment, the *Robot* group scores better averaging results as compared to the *Tablet* group (*Robot* (M=5.48, SD=0.509) and *Tablet* (M=4.72, SD=0.343)). Figure 6.10 presents the visual results of 'Perceived Intelligence'.

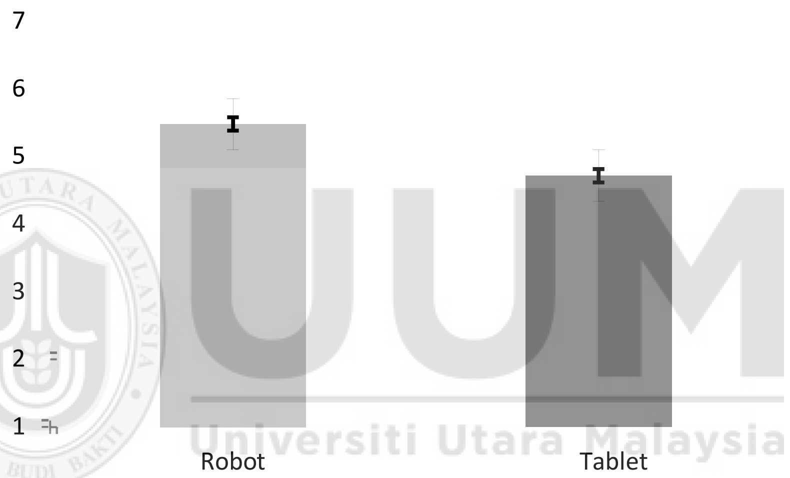

Figure 6.10. Results for Perceived Intelligence

Descriptive analysis is not adequate to show the significant difference between the mean values. Therefore, inferential statistical analysis was performed in the form of an independent *t*-test. To achieve this analysis, a hypothesis was formulated as follows.

$$H1: \mu_{PIRmean} > \mu_{PITmean}$$

$$H0: \mu_{PIRmean} \leq \mu_{PITmean}$$

The hypothesis H1 suggests that participants in *Robot* group perceived IQRA' as a more intelligent platform comparing to a Tablet platform. Conversely, the null hypothesis H0 proposes that participants in *Tablet* group perceive the tablet platform identical or more intelligent than a robotic platform. An independent *t* test analysis results indicated that the difference between the mean values (*Robot* (M=5.48, SD=0.509) and *Tablet* (M=4.72, SD=0.343)) is significant, t (18) =3.9, p<0.001. This result confirms the descriptive analysis and showed the robotic platform is perceived as having some degree of intelligence compared to the tablet platform. The underlying idea of this result is due to robot's ability to express more salient and fluid human-like behaviours in terms of its sociability, social presence, and animacy as discussed in next sections. The tablet platform has lesser capability to express those concepts due to limitation in physical embodiment activities.

Sociability

Sociable feature is one of the crucial factors to be incorporated in maintaining human-robot interaction in socially accepted manners. It is also one of the precursors to regulate better social interaction between human and robot. The descriptive results were obtained as the following; *Robot* (M=5.43, SD=0.646) compared to *Tablet* (M=3.4, SD=0.775). Figure 6.11 depicts the results for experiments in sociability.

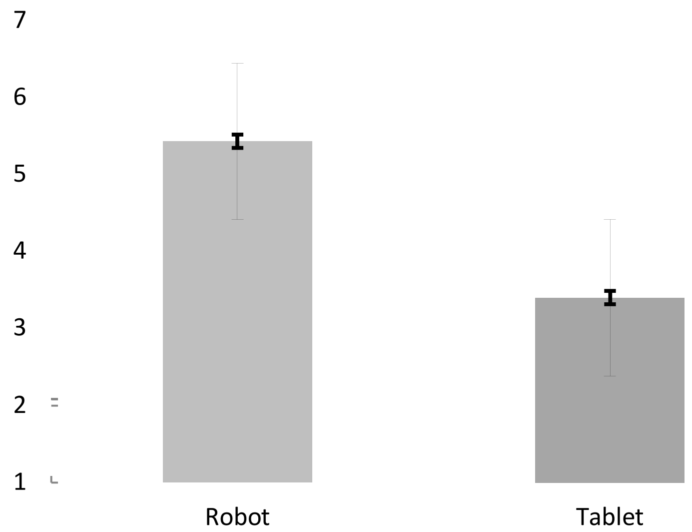

Figure 6.11. Results for Sociability

In addition to this, respondents in the experiment group were asked to rate the animacy (based on 7-points semantic differential scale) for IQRA' and resulted as (M=5.02, SD=0.38).

In addition to the descriptive analysis, efforts were made for further inferential statistical analysis to determine if participants in *Robot* group perceived the sociability of the robotic platform significantly higher compared to *Tablet* platform. For this, a hypothesis was suggested and an independent *t* test analysis (i.e., between participants) was performed. The hypothesis was formulated as follows.

$$H1: \mu_{SRmean} > \mu_{STmean}$$
$$H0: \mu_{SRmean} \leq \mu_{STmean}$$

The hypothesis H1 proposes that participants perceive the robotic platform has more sociability characteristics over the Tablet platform ($\mu_{SRmean} > \mu_{STmean}$). The *t* test analysis results rejected the null hypothesis as it found that the difference in perceiving sociability of the robot is significant, $t(18) = 6.4$, $p<0.001$. The obtained results from the descriptive and inferential analysis is consistent with the findings from almost similar works (Mann, MacDonald, Kuo, Li, & Broadbent, 2015; Paauwe, Hoorn, Konijn, & Keyson, 2015) where most of the robotic platforms score higher sociability rating compared to other platforms (e.g., tablet, computer screen).

Social Presence

The social presence is imperative as a basis to allow social acceptance between human-robot interactions. Both of sociability and social presence were considered as an indicator to measure user's social acceptance level. Social presence is defined in the sense of users' perception during the interaction with any digital artefacts, whether they view the artefact as a social entity or not (Heerink et al., 2009). The results from the descriptive analysis have shown scores for *Tablet* (M=2.82, SD=0.791) and *Robot* (M=5.12, SD=0.627). Figure 6.12 presents the results from this experiment.

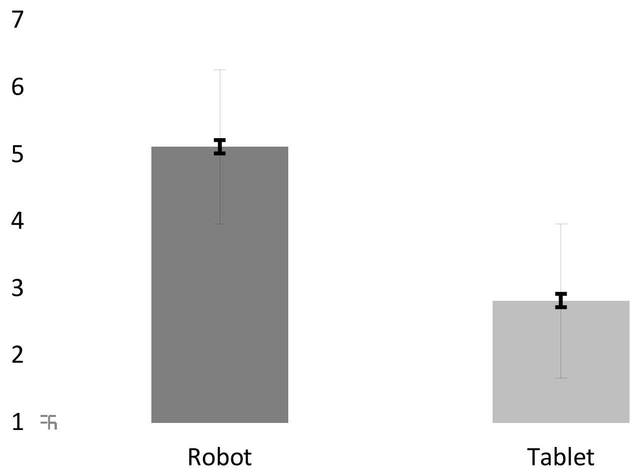

Figure 6.12. Results for Social Presence

Similar to the analysis in perceived sociability, an independent *t* test analysis was achieved to recognise the difference in mean values from the descriptive analysis is significant or not. To attain this, a hypothesis was formulated as follows.

$$H1: \mu_{SPRmean} > \mu_{SPTmean}$$
$$H0: \mu_{SPRmean} \leq \mu_{SPTmean}$$

The hypothesis H1 recommends that participants in *Robot* group perceive the robotic platform having more features of "*Social Presence*" compared to the *Tablet* platform. This null hypothesis H0 was rejected and the alternative hypothesis was confirmed as the analysis results found the variance in mean values between the two groups is significant, t (18) =7.2, p<0.001. The results are consistent with previous empirical studies that investigated the sociability of physical robot against the animated character (Wainer et al., 2006; Berland & Wilensky, 2015).

Perceived Usefulness

The construct for ”Usefulness” is defined as “the degree to which a person believes that using the system would enhance his or her daily activities” (Heerink et al., 2009). Figure 6.13 depicts the analysis results for both *Robot* and *Tablet*.

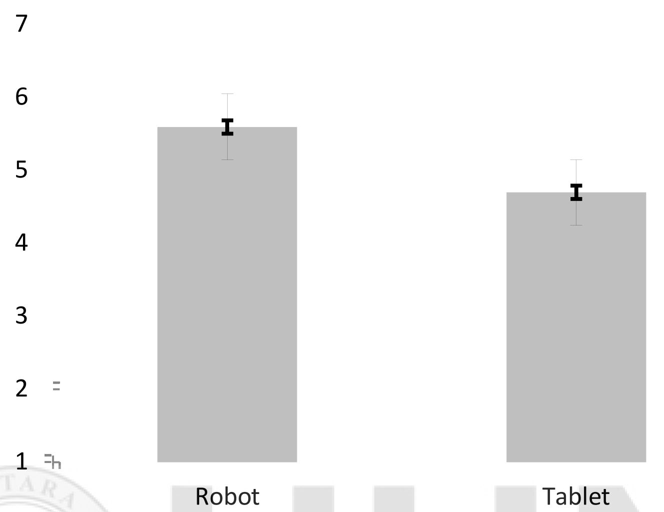

Figure 6.13. Results for Perceived Usefulness

The obtained result (*Robot* (M=5.7, SD=0.7) and *Tablet* (M=4.7, SD= 0.48) of perceived usefulness is consistent with the previous results, where both platforms were seen useful and capable to reduce cognitive load as discussed in Section 6.2.2.2. However, the robot-based platform received better perceived usefulness rating than tablet-based platform. The fundamental idea behind this result is the robot capable of displaying intelligent characteristics, being sociable and embodied presence.

6.2.2.4 Usability

For this experiment, ten items were used based on 7-points Likert scale ranging from scale 1 (for “strongly disagree’’) to scale 7 (to represent “strongly agree’’). The results (as depicted in Figure 6.14) have shown that the usability test for both platforms was high and consistent. The scores for both platforms are; *Robot* (M=6, SD=0.47) and *Tablet* (M=5.9, SD=0.31).

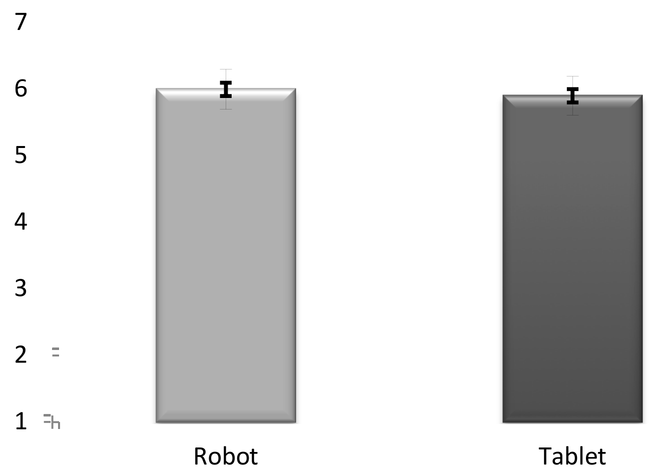

Figure 6.14. Results for Usability Test

The results could be viewed as the ambient agent model works well for both platforms.

6.2.2.5 Ratings and Semi-Structured Analysis

At the end of the experiment, participants in the experimental group were interviewed using both semantic differential scale and loosely structured interview. There were three questions (based on 7-point semantic differential scale) were asked to capture respondents' perception pertinent to their interaction with IQRA'. These questions cover important aspects in *Desire to Continue*, *Satisfaction with the Provided Support*, and *Motivation*. The average value of the respondents' ratings was positive as presented in Table 6.1.

Table 6.1

Ratings of the Reading Companion Robot

Measurement Construct	Min(1)	Max(7)	Mean (M)	Std. Deviation (SD)
Desire to Continue	Not at all	Very much	5.64	0.809
Satisfaction	Not at all	Very much	5.64	0.674
Motivation	Not at all	Very much	5.82	0.981

Also, the identical results were confirmed from the conducted interview where most of the respondents have reported that they were excited to continue using the companion robot. They were reported satisfied with the support provided by the robot and perceived as the robot was able to motivate them during the session. Here, some examples of the respondents' feedbacks after using IQRA'.

> **Respondent #1:** "Y*es, I found it interesting and I would like to have it one at home. It is friendly and helped me to figure out how to solve the task. It motivates me to keep it up my work and I like this".*

> **Respondent #4:** *"Yes, it is nice, friendly, and helpful…I would like to use it more. It helps me when I feel…I can't solve the task. I like the way it praised me, awesome!"*

> **Respondent #6:** "*of course, I can use it, especially to solve my assignments. I am satisfied with the provided supports!. Yes, it motivates me like my friend. I like it."*

> **Respondent #9:** **"***Absolutely***,** *I want to continue using it to see its potentials…it seems intelligent. Yes…yes. I am very satisfied. Indeed..*, *I even smiled when it praised me. I think it knows how to motivate the students like me".*

6.2.3 Results Discussion

This section summarizes the experimental results from two angles; first, the effect of the ambient agent model in reducing cognitive load. Second, how it is related to the admissible evidences from integrating this model into a robotic platform (rather than the *Tablet* alone). From the applicability of an ambient agent model, both of these platforms have reduced cognitive load among respondents. These positive results provide an indication that the ambient agent model was designed in an appropriate manner to reason and provide suitable support or interventions to readers. Furthermore, the support effectiveness provided by the robot was found to be slightly better.

From the acceptance perspective, the findings shown robot-based platform is a good choice for the implementation of an ambient agent model engine due to its ability to display likeability, intelligence, sociability, social presence, and animacy constructs. These constructs received lower score for a tablet-based platform.

6.3 Summary

This chapter illustrated important activities for the evaluation phase. First, it begins with the mathematical analysis to evaluate the cognitive agent model, which a stability analysis was conducted. Later, the model was automatically validated internally using a Temporal Trace Language (TTL), which cases from related literature were used. Next, the designed ambient agent model was evaluated using the same concept as in TTL.

Furthermore, the human experiment was conducted to evaluate the implementation of a reading companion robot (IQRA') based on an ambient agent model. The experimental results have shown that the ambient agent model was able to reduce cognitive load during reading and solving demanding tasks. Moreover, the design of the reading companion robot received positive feedbacks from respondents as it has seen as a likeable, sociable, intelligent, and useful while supporting readers to solve cognitively demanding readings tasks. Next chapter concludes overall findings and achieved objectives.

CHAPTER SEVEN
CONCLUSION

This chapter summarizes significant findings related to the intended objectives that were addressed in Chapter One. Discussion on the impact of this study and future work also has been described. This chapter is organized as follows. Section 7.1 summarizes the contributions from other preceding chapters' discussions while the implication of this study is presented in Section 7.2. Later, Sections 7.3 describe the future work of this study.

7.1 Accomplishment of the Objectives

The main objective of this study is to design a computational model that demonstrates the mechanism of ambient agent models based on human functional states (physical and cognitive process) as a reasoning engine for reading companion robots. The main objective was constructed based on four sub-objectives, namely; (1) to develop a computational cognitive agent model based on analysing psycho-cognitive factors and its relationships of cognitive load and reading performance, (2) to develop an ambient agent model for cognitive load and reading performance based on the developed cognitive agent model, (3) to develop integration algorithms to integrate the developed ambient agent model into a reading companion robot, and (4) to evaluate the ambient agent model and its implementation within a reading companion robot context. These four objectives have been accomplished and a summary of these findings is covered in this chapter.

RO1: Research Objective One

"To develop a computational cognitive agent model based on analysing psycho-cognitive factors and its relationships of cognitive load and reading performance"

This first objective analysed related factors and its relationships of cognitive load and reading performance to explain the dynamics of cognitive load and reading performance derived from psychological and cognitive science point of views. In this study, thirty-three (33) factors and its interplays related to cognitive load and reading performance were obtained and explained. Moreover, the analysed factors were conceptualized and formalized to develop a computational cognitive agent model to understand the mechanism behind cognitive load and reading performance. This was achieved using a *Network Oriented Modelling* approach that utilizes the Temporal Causal Networks concept. Later, this model was coded in a numerical programming tool for simulation purposes. The model conceptual design, formal specifications, and simulation results were explained in Chapter Four. The obtained cognitive agent-based model (or domain model) provides full insights about the dynamical mechanism of a cognitive load process and its negative ramifications such as exhaustion, persistence, and disengagement while performing demanding reading tasks.

RO2: Research Objective Two

"To develop an ambient agent model for cognitive load and reading performance based on the developed cognitive agent model"

The second objective has been achieved through the formalization of an ambient agent model of cognitive load and reading performance which was developed based on the understanding of human's physical and cognitive states (i.e., the developed cognitive agent model as stated in RO1). As a first step to develop the ambient agent model, supporting factors that reduce the onset of cognitive load and its negative consequences were analysed and determined. Towards this, five (5) supporting factors that reduce cognitive load effects were found.

The Belief-Desire-Intention (BDI) concept and First-Order Predicate Logic (FOPL) provide a backbone towards the development of an ambient agent model through the underlying construct of an agent-based model and related supporting factors. By incorporating an ambient agent model in software systems, it gives them a form of understanding of humans encompasses the analysis of the humans' cognitive state and dynamics in relation to the modelled processes. Based on this knowledge, these smart systems may provide intelligent support in an informed way and in a timely fashion (Bosse et al., 2012; Both et al., 2015; Duell, 2016; Treur, 2016b; Klein et al., 2017).

Different models were developed and constructed based on the developed cognitive agent model (domain model). These models are; 1) a Belief Base model, 2) an Analysis model, 3) a Support model, and 4) a Domain model. Later, the ambient agent model was formalized using Predicate Calculus (First-Order Predicate Logic) where the model's ontologies were specified. The ontologies provide a basis to develop a set of temporal rule specifications. These specifications were used for simulations using a Temporal Language called LEADSTO simulation traces generation. This second objective was achieved in Chapter Five.

RO3: Research Objective Three

"To develop integration algorithms to integrate the developed ambient agent model into a reading companion robot"

The designed ambient agent model in RO2 is transformed into six algorithms for integration purposes into a robotic software system. These algorithms serve as an underlying analytical tool in monitoring and analysing reader's performance to generate related support actions as discussed in Chapter Five (Section 5.6). Next, an attempt was accomplished to design a companion robot based on the ambient agent (software agent).

Companion robots have attracted numbers of research interests and development to create better quality of life. The central point of such interests is due to its abilities to perform many tasks in a socially acceptable manner. In this study, results from a survey have shown that a table lamp-like design was preferred mediated object to be presented as a reading companion robot. The developed robot is called IQRA' and has an Android-based smartphone for its computational processing units, a table lamp stands as a base, a Raspberry Pi platform as a microcontroller, and servo and DC motors with 4-DOF. Chapter Five covers the detailed descriptions of the IQRA' design and its synchronization process between software and hardware components.

RO4: Research Objective Four

"To evaluate the ambient agent model and its implementation within a reading companion robot context"

This objective has been achieved through verification and validation for both formal models and robotic implementation. During the verification stage, a mathematical analysis procedure (equilibrium analysis) was implemented to prove the correctness of the formal specifications within a cognitive agent model (as discussed in Section 6.1.1). Subsequently, the verified cognitive agent and ambient agent models were internally validated using Temporal Trace Language (TTL). TTL allows an automated validation of the specified properties (from the literature and existing empirical experiments) and states against generated traces (Section 6.1.2 and 6.1.3). The external validation process was conducted to evaluate several important constructs as in Section 6.3. In this stage, 20 undergraduate students from School of Computing, Universiti Utara Malaysia were selected using a purposive sampling technique based on voluntarily basis. The questionnaire survey was adopted as a data collection method (as in Chapter Three). The experiment process was divided into two groups; control and experimental. Both groups were asked to solve the "Tower of Hanoi puzzle" within an hour. Both groups (control vs. experiment) were exposed only either to a tablet or robot-based platform respectively. Throughout the experiment, respondents' cognitive load level was measured for different time frames. This is crucial in accessing the impacts of support provided by an ambient agent model. Towards this end, a set of questionnaires was used to measure respondents' perceptions towards the reading companion robot. Chapter Six detailed up the discussion of these findings and Table 7.1 summarizes the different evaluation techniques have been undertaken to accomplish this objective.

Table 7.1

Evaluation Techniques for the Study

Evaluated Components	**Mathematical Analysis**	**Automated Logical Analysis**	**Human Experiment**
Cognitive agent model	X	X	
Ambient agent model		X	
Reading companion robot			X

Table 7.2 provides a summary of the study objectives accomplishment throughout different chapters of this study.

Table 7.2

The Objectives Achievement and Its Related Chapters

Chapter / Research Objective	Objectives			
	RO1	**RO2**	**RO3**	**RO4**
Chapter One				
Chapter Two				
Chapter Three				
Chapter Four	X			
Chapter Five		X	X	
Chapter Six				X
Chapter Seven				

7.2 Implications of the Study

The contributions of this study can be presented in five ways. First, this study has paid explicit attention towards exploring the cognitive load factors that hampered reading performance while acquiring new knowledge (i.e., when learning process has occurred). Although several previous trials were attempted to explain these cognitive load precursors, little attention was paid to explain the interplays and dynamic mechanism between these underlying factors. Therefore, this study has contributed to explain the interplays between these factors in a computational manner.

Second, the study has contributed in providing a formal specification and analysis of cognitive load and reading performance by introducing a computational model of cognitive load and reading performance. The obtained computational model also can be used by scientists from psychology and cognitive science to deeply investigate the temporal dynamics cognitive load through computer simulations. Third, this study has made a significant contribution within ambience intelligence fields. It has demonstrated how dynamic models about humans' cognitive and physical processes can be integrated to create ambient intelligent applications in providing appropriate interventions in well-informed manners.

Moreover, this study has made the fourth contribution in the field of companion robots. The study has substantially succeeded in designing a reading companion robot called IQRA' that can support readers by making their reading process seamless and meaningful. This study has confirmed that the companion robotic reasoning engine can be developed based on cognitive and ambient agent models. Furthermore, the study has also contributed to the body of knowledge in companion robots to support findings in previous empirical studies (e.g., to prove that physical embodiment plays a significant role in increasing social competency).

The final contribution of the study was achieved through the design of a general model (as stated in Section 5.1) that demonstrates how ambient agent models can be integrated with companion robots. This generic model can serve as a design guideline to help roboticists or agent-mediated platform in designing any companion robots based on related ambient agent model. For example, this generic model can be used as a guideline to design a therapeutic companion robot to alleviate stress by utilizing an ambient agent model of stress.

These five contributions of the study have broadened the horizon of ambience intelligence and companion robots research. The current study has brought both ambience intelligence and robotic technology together through artificial intelligence systems in developing an intelligent robotic application incorporate more in-depth analysis of human functioning and assist humans in a social manner.

7.3 Future Work

To attain the study main objective, an ambient agent model explaining how human functioning models can be integrated into companion robots was developed. Thus, the designed robots can have the ability to reason and perform analysis in the same way human do and base on this analysis a personalize intelligent support can be given in a socially accepted manner. Based on this concept, the study has successfully created a reading companion robot as a proof-of-concept for the future work in creating companion robots that will be increasingly useful in the everyday lives of many people. Regarding this study, suggested future work will continue towards three major directions as follows.

a. Human-Robot-Interaction

The future of this type of research is related to study the details of human-robot interaction concepts to allow better fluency using social-directed cues. Precisely, a full sensor-based system is necessary to create fluent and smooth interaction. For example, the implementation of face recognition, motion detection, and in addition ambient sensors to be used to observe reader's conditions in non-intrusive manners such as light, temperature, and noise sensors.

b. Integration of the Ambient Agent Model with other Models

This study aims for future endeavours at expanding the ambient agent model by incorporating additional human functioning models. For example, next study should be towards developing a cognitive agent model for emotion impacts during demanding reading tasks. This will enable the reading companion robot to react intelligently and provide wide range of interventions that help readers to experience better and seamless reading processes.

c. Deep Learning

Deep learning techniques can be extended to the reasoning engine of the robot to provide self-referencing dataset for an intelligent support process. Therefore, the reasoning engine can be personalized for each individual and better analytical mechanism can be used as the engine will be able to discern hidden patterns throughout time.

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Appendix A
Consent Form

Dear participant,

You are asked to participate in an experimental research conducted by Hayder Mohammed Ali, doctoral candidate, Azizi Ab Aziz, *Ph.D.*, and Faudziah Ahmad, *Ph.D.*, from School of Computing at Universiti Utara Malaysia (UUM). The result of this experiment will be used as an essential part in the doctoral thesis of Hayder Mohammed Ali. You were selected as a possible participant in this research because you have indicated that you are ready to provide identical feedback which is extremely appreciated in evaluating a reading companion robot that was developed to accompany and assist readers during their reading. You should read the provided information below, and ask questions about anything you don't understand before proceeding to participate. Your participation in this experiment is highly respected and you are free to decide whether to be in it or not.

- **PURPOSE OF THE RESEARCH**

The main goal of this experimental study is to evaluate the first prototype of a reading companion robot that called IQRA'. It was developed to support readers during reading tasks. The obtained results of this experiment will help to validate to what extend the designed robot is accepted and useful to help readers.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this survey and that can be identified with you will remain confidential and will be used only for research purpose.

- **IDENTIFICATION OF RESEARCHERS**

If you have any additional questions or concerns about this survey, please feel free and do not hesitate to contact:

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Appendix B

Survey Evaluation Items

I. DEMOGRAPHIC DETAILS (Please mark (√) in the appropriate place provided)

1. Gender?

☐ Male ☐ Female

2. Nationality**?**

☐ Malaysian ☐ Not Malaysian, state …………………

3. Email address……………………………………….

4. Age group?

☐15-20 ☐21-30 ☐31-40 ☐ > 40

5. Highest Education level?

☐ Diploma ☐ Matriculation/STPM/A level ☐ High Secondary School

II. THE ROBOT USABILITY MEASUREMENT

Instruction: For each of the following statements, please circle the number that best describes your reactions toward using IQRA':

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

1. I think that I would like to use the robot frequently.	1	2	3	4	5	6	7
2. I found the unnecessarily complex.	1	2	3	4	5	6	7
3. I thought the robot was easy to use.	1	2	3	4	5	6	7
4. I think that I would need assistance to be able to use the robot.	1	2	3	4	5	6	7
5. I found the various functions in the robot were well integrated	1	2	3	4	5	6	7
6. I thought there was too much inconsistency in the robot.	1	2	3	4	5	6	7
7. I would imagine that most people would learn to use the robot very quickly.	1	2	3	4	5	6	7
8. I found the robot very cumbersome/ awkward to use.	1	2	3	4	5	6	7
9. I felt very confident using the robot.	1	2	3	4	5	6	7
10. I needed to learn a lot of things before I could get going with the robot.	1	2	3	4	5	6	7

III. PERCEPTION TOWARD THE DEVELOPED ROBOT

Instructions: For each of the following sub-sections, please circle the number that best describes your impression toward IQRA'.

SECTION A: Please rate your impression of the robot on these scales:

a) Perceived Likeability

Dislike	1	2	3	4	5	6	7	Like
Unfriendly	1	2	3	4	5	6	7	Friendly
Unkind	1	2	3	4	5	6	7	Kind
Unpleasant	1	2	3	4	5	6	7	Pleasant
Awful	1	2	3	4	5	6	7	Nice

b) Perceived Intelligence

Incompetent	1	2	3	4	5	6	7	Competent
Ignorant	1	2	3	4	5	6	7	Knowledgeable
Irresponsible	1	2	3	4	5	6	7	Responsible
Unintelligent	1	2	3	4	5	6	7	Intelligent
Foolish	1	2	3	4	5	6	7	Sensible

c) Perceived Animacy

Dead	1	2	3	4	5	6	7	Alive
Stagnant	1	2	3	4	5	6	7	Lively
Mechanical	1	2	3	4	5	6	7	Organic
Artificial	1	2	3	4	5	6	7	Lifelike
Inert	1	2	3	4	5	6	7	Interactive
Apathetic	1	2	3	4	5	6	7	Responsive

SECTION B: For each of the following statements, please circle the number that best describes your opinion toward using the developed robot,

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

• **Perceived Sociability**							
1. I consider the robot a pleasant conversational partner.	1	2	3	4	5	6	7
2. I find the robot pleasant to interact with.	1	2	3	4	5	6	7
3. I feel the robot understands me.	1	2	3	4	5	6	7
4. I think the robot is nice.	1	2	3	4	5	6	7
• **Perceived Usefulness**							
5. I think the robot is useful to me.	1	2	3	4	5	6	7
6. It would be convenient for me to have the robot.	1	2	3	4	5	6	7
7. I think the robot can help me with many things.	1	2	3	4	5	6	7
• **Social Presence**							
8. When interacting with the robot I felt like I'm talking to a real person.	1	2	3	4	5	6	7
9. It sometimes felt as if the robot was really looking at me.	1	2	3	4	5	6	7
10. I can imagine the robot to be a living creature.	1	2	3	4	5	6	7
11. I often think the robot is not a real person.	1	2	3	4	5	6	7
12. Sometimes the robot seems to have real feelings.	1	2	3	4	5	6	7

SECTION C: For each of the following statements, please circle the number that best describes your opinion toward using the developed robot.

1. I would like to continue using the robot.	Not at all	1	2	3	4	5	6	7	Very Much
2. I am satisfied with support given by the robot	Not at all	1	2	3	4	5	6	7	Very Much
3. The robot was able to motivate me.	Not at all	1	2	3	4	5	6	7	Very Much

SECTION D: Cognitive Load Measurement: Please circle the number that best describes the difficulty of the task?

Very, very easy 1 2 3 4 5 6 7 Very, very difficult

Appendix C

Formal Specifications in the Integration Algorithm

NOMENCLATURES OF AGENT'S OBSERVATIONS

No	Agent's observations	Representation
1	Agent observes reading task	*o*(*A*, *Rt*)
2	Agent observes academic level	*o*(*A*, *Al*)
3	Agent observes Subject matter	*o*(*A*, *Sr*)
4	Agent observes Sound	*o*(*A*, *Sd*)
5	Agent observes duration to complete	*o*(*A*, *Ra*)
6	Agent observes graphical presentation	*o*(*A*, *Gp*)
7	Agent observes brightness	*o*(*A*, *Br*)
8	Agent observes comprehensive information	*o*(*A*, *Ci*)
8	Agent observes temperature	*o*(*A*, *Te*)

NOMENCLATURES OF AGENT'S BASIC BELIEFS

No	Agent's basic beliefs	Representation
1	Agent believes reading	*b*(*A*, *Ra*)
2	Agent believes task level	*b*(*A*, *Tl*)
3	Agent believes study subject matter	*b*(*A*, *Ss*)
4	Agent believes adequate time	*b*(*A*, *Ad*)
5	Agent believes task structure	*b*(*A*, *Ts*)
6	Agent believes noise	*b*(*A*, *Ns*)
7	Agent believes ambient temperature	*b*(*A*, *At*)
8	Agent believes lighting	*b*(*A*, *Ln*)
9	Agent believes personality	*b*(*A*, *Ps*)
10	Agent believes task familiarity	*b*(*A*, *Tf*)
11	Agent believes exposure	*b*(*A*, *Ep*)
12	Agent believes basic knowledge	*b*(*A*, *Bk*)
13	Agent believes reading skills	*b*(*A*, *Rs*)
14	Agent believes language competency	*b*(*A*, *Lc*)
15	Agent believe time spent	*b*(*A*, *Ts*)

NOMENCLATURES OF AGENT'S DERIVED BELIEFS

No	Agent's derived beliefs	Representation
1	Agent believes reading task complexity	*d*(*A*, *Tc*)
2	Agent believes time pressure	*d*(*A*, *Tp*)
3	Agent believes task presentation	*d*(*A*, *Tn*)
4	Agent believes physical environment	*d*(*A*, *Pe*)
5	Agent believes personal profile	*d*(*A*, *Pp*)
6	Agent believes experience level	*d*(*A*, *El*)
7	Agent believes prior knowledge	*d*(*A*, *Pk*)
8	Agent believes reading norm	*d*(*A*, *Rn*)

NOMENCLATURES OF AGENT"S ASSESSMENTS

No	Agent's assessments	Representation
1	Agent assesses cognitive load	*a*(*A*, *Cl*)
2	Agent assesses persistence	*a*(*A*, *Pr*)
3	Agent assesses accumulative exhaustion	*a*(*A*, *Ae*)
4	Agent assesses reading performance	*a*(*A*, *Rp*)

NOMENCLATURES OF AGENT'S DISPLAY TO THE READER

No	Agent's display	Representation
1	Agent displays the first confirmation to confirm room conditions	$s(A, Cp_i)$
2	Agent displays the second confirmation to tell the actual belief on environment condition	$s(A, Cp_{i+1})$
2	Agent display the confirmation to confirm reader's conditions	$s(A, Cc)$
3	Agent displays the first confirmation to confirm the reader is exhausted	$s(A, Ce_i)$
4	Agent displays the second confirmation to tell the actual belief on exhaustion	$s(A, Ce_{i+1})$
5	Agent display the first confirmation to confirm the low level of persistence	$s(A, Cs_i)$
6	Agent display the second confirmation to confirm the low level of persistence	$s(A, Cs_{i+1})$

NOMENCLATURES OF AGENT'S ACTIONS TO THE READER

No	Agent's actions	Representation
1	Agent advises to make the environment ambience	*v*(*A, Am*)
2	Agent provides praising for good progress	*p*(*A, Pg*)
2	Agent provides praising for maintaining good progress	*p*(*A, Pm*)
3	Agent advises for short break	*v*(*A, Sb*)
4	Agent provides motivational talk	*p*(*A, Mt*)

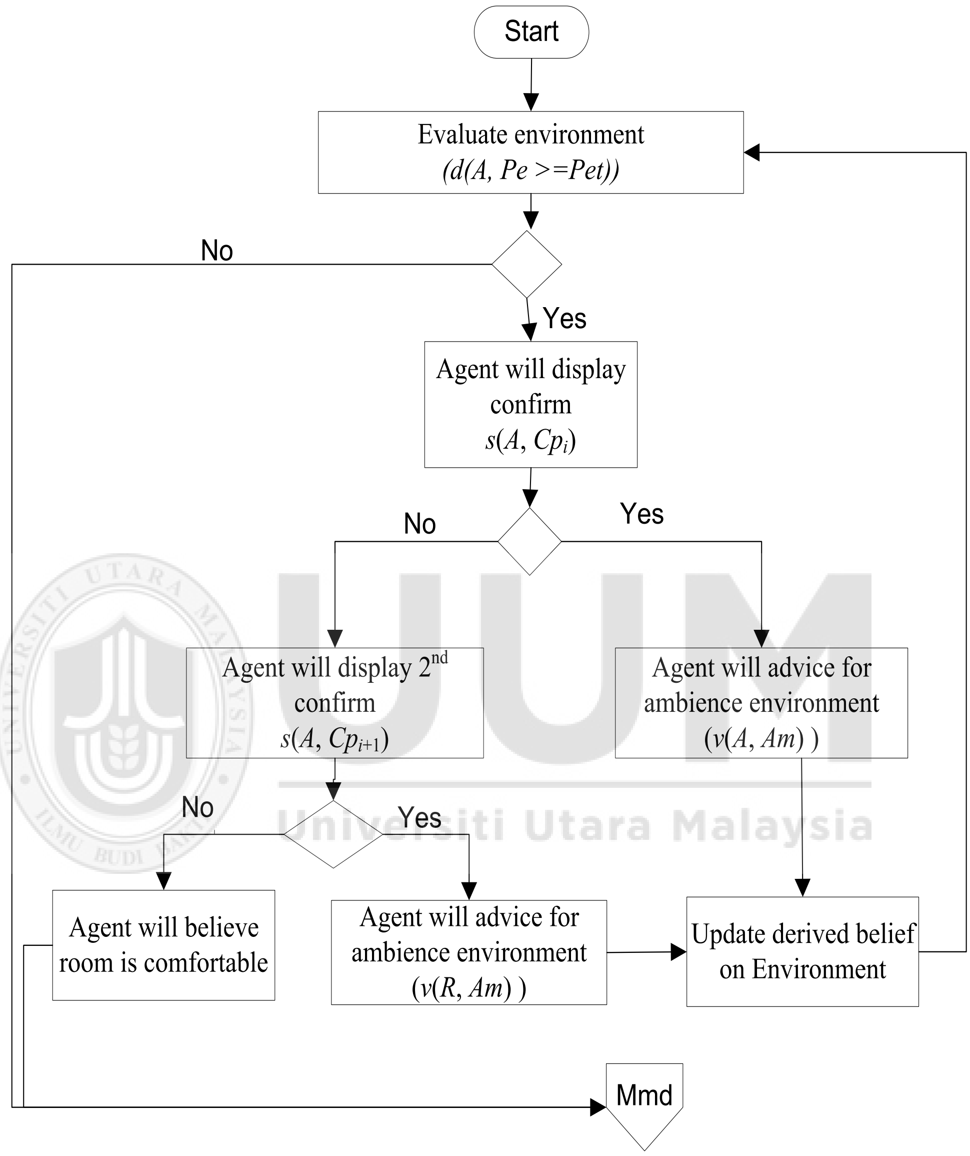
NOMENCLATURES OF AGENT'S EVALUATION ON READER'S CONDITIONS

No	Reader conditions	Representation
1	An Agent performs constant checking	*f*(*A*, *Cc)*
2	Agent displays a confirmation screen	*s*(*A*, *Cr*)
2	Agent evaluates whether a reader experiences high cognitive load	*e(r, Hcl)*
3	Agent evaluates whether a reader experiences high exhaustion	*e(r, Hae)*
4	Agent evaluates whether a reader experiences low persistence	*e(r, Lpr)*

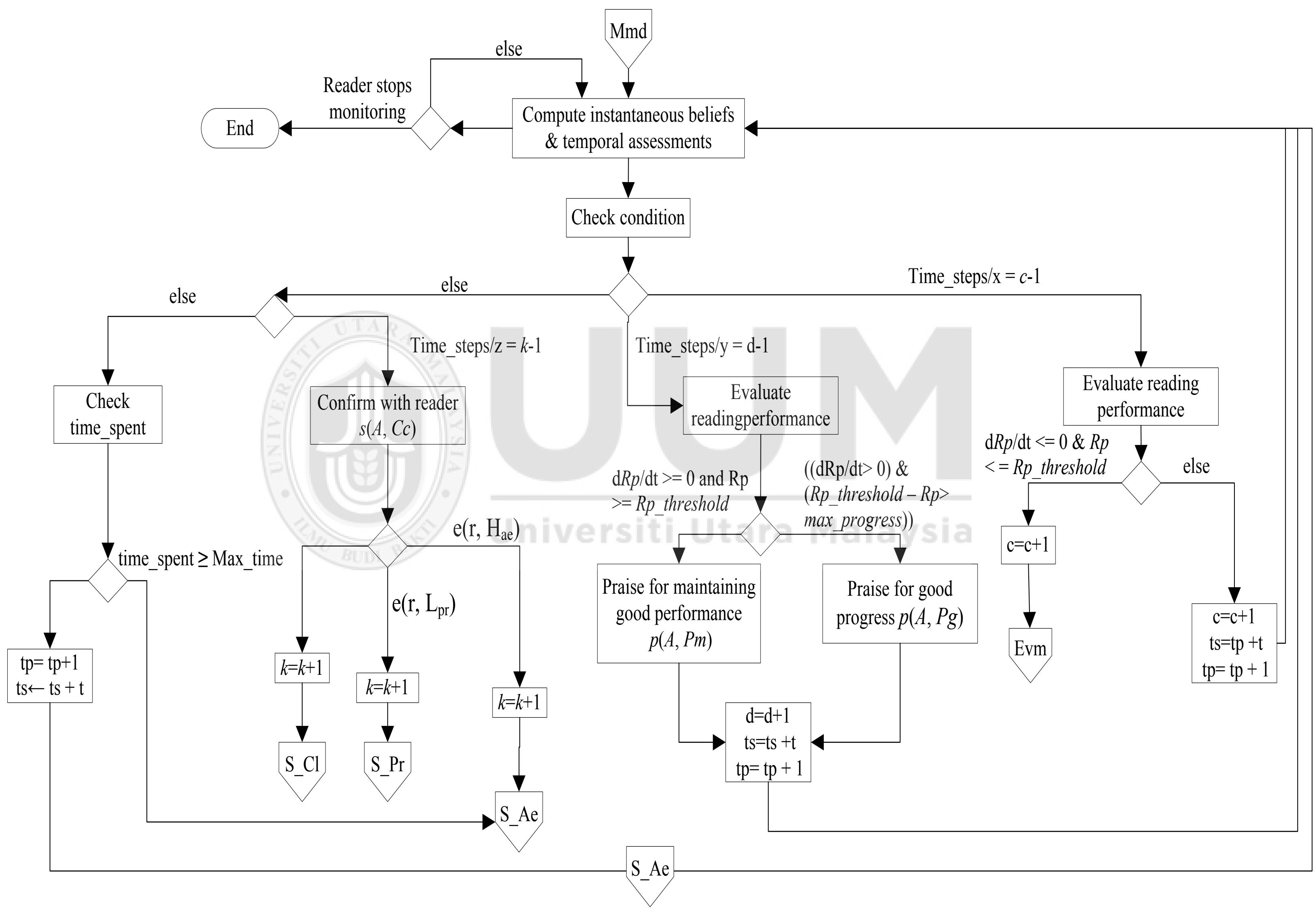
Appendix D

Integration Modules Flow Charts

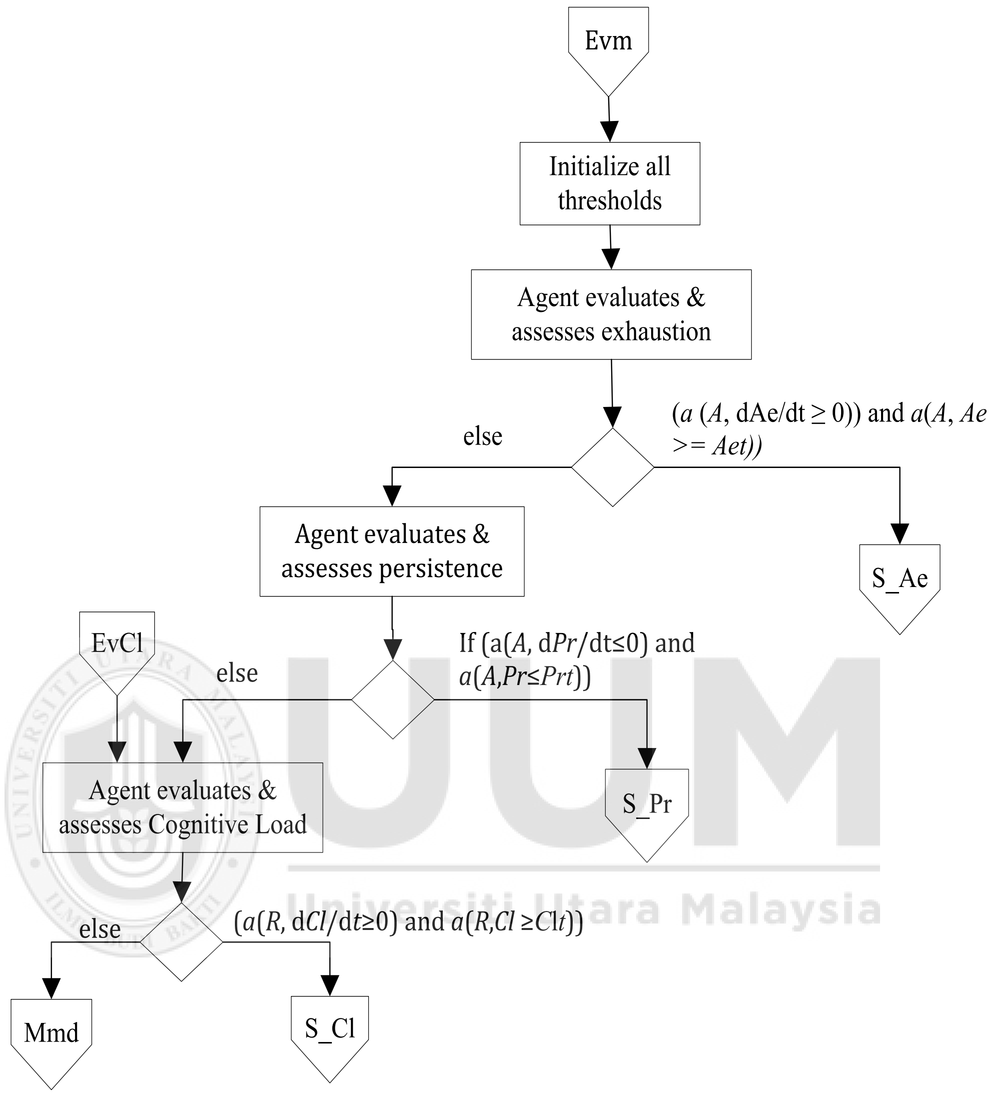
ENVIRONMENT EVALUATION FLOW CHART



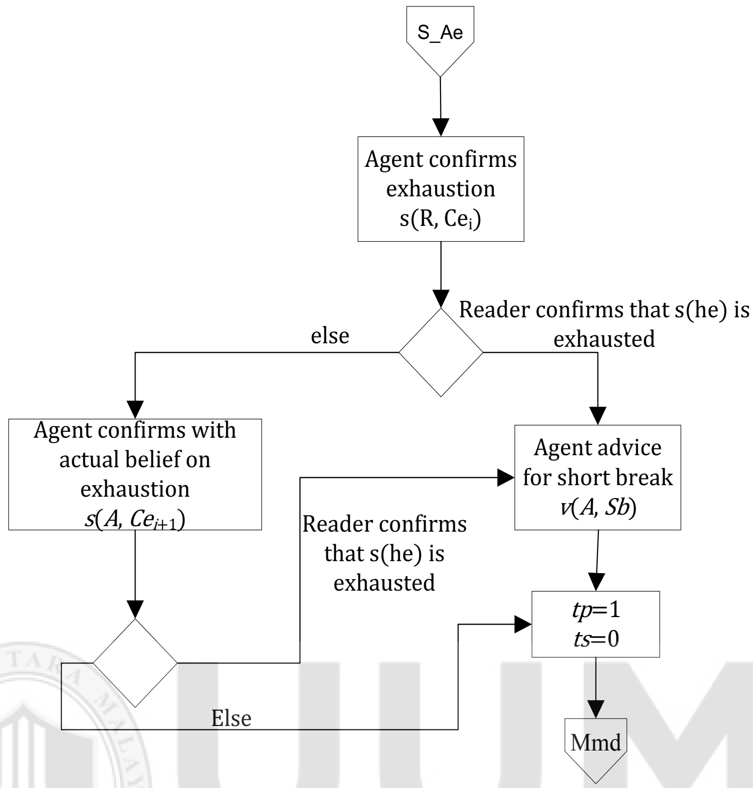
MONITORING MODULE FLOW CHART



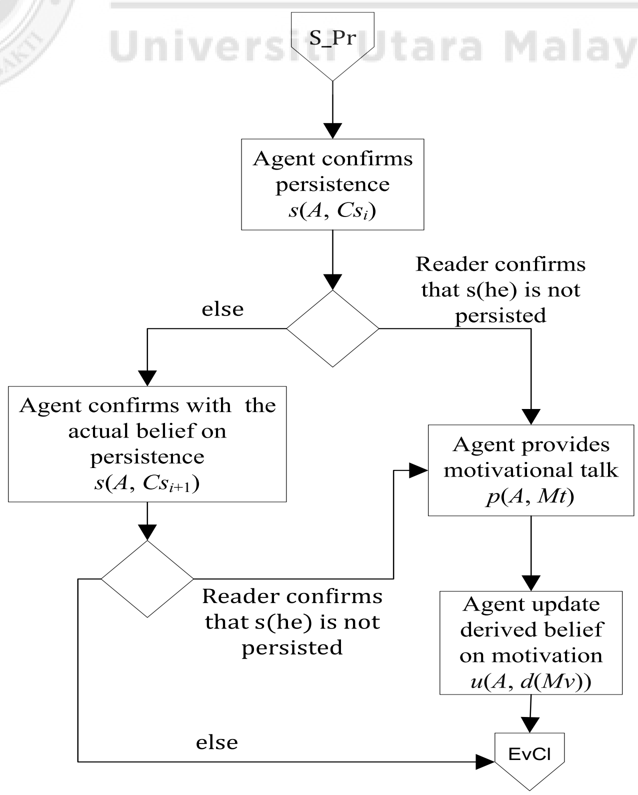
EVALUATION MODULE FLOW CHART



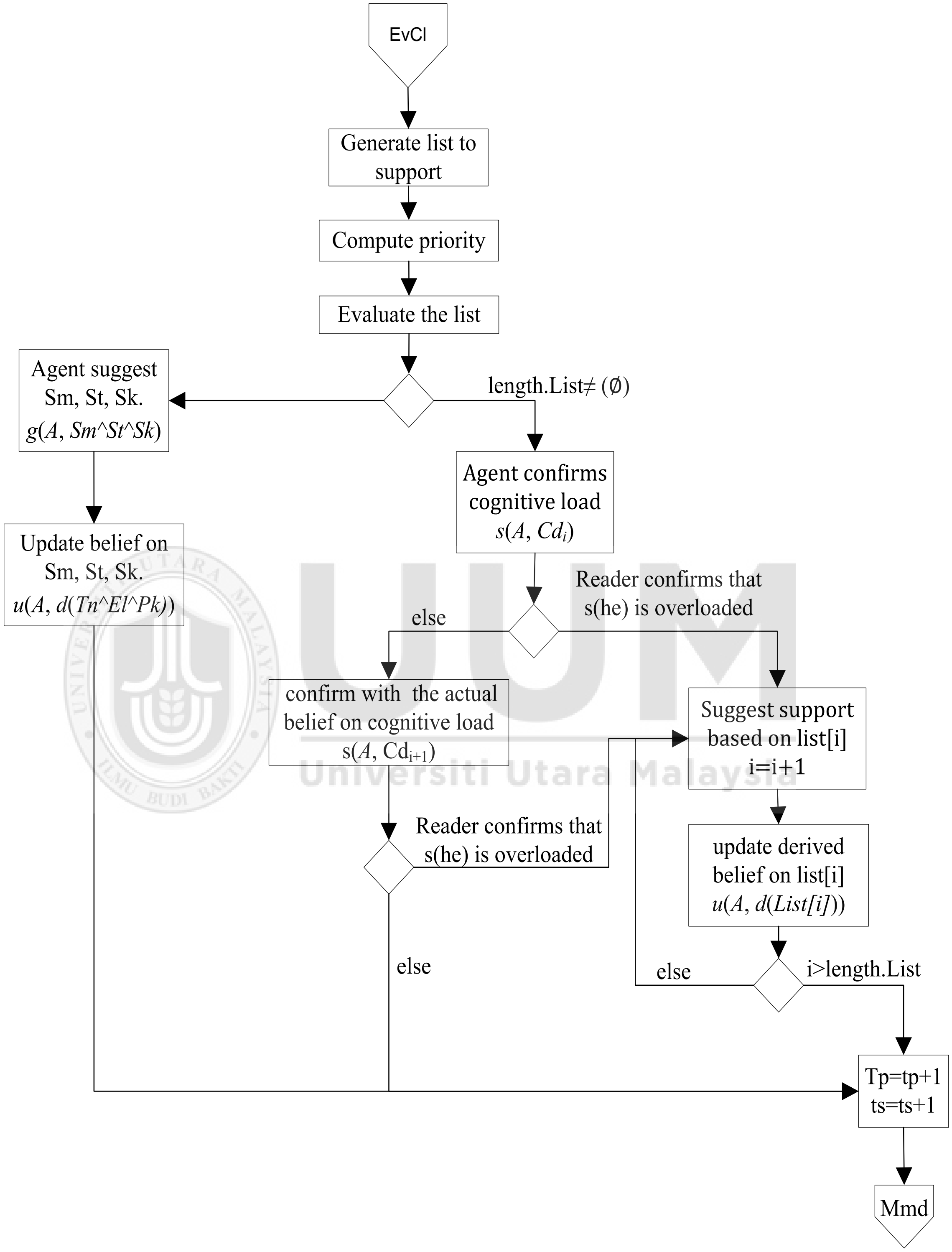
EXHAUSTION SUPPORT MODULE



PERSISTENCE MODULE FLOW CHART



COGNITIVE LOAD MODULE FLOW CHART



Appendix E

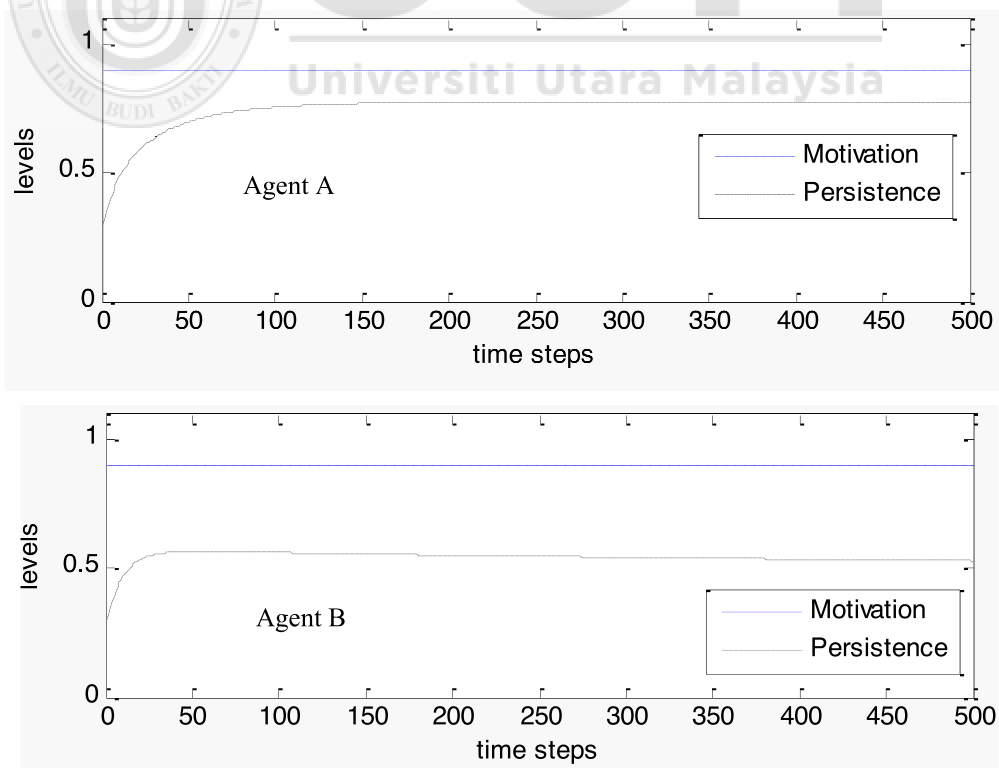
Further Simulation Results

1) Simulation Results for Cognitive Agent Model

a) Motivation and Persistence

The simulation traces pertinent to motivation and persistence are presented based on different settings for two fictional agents as follows.

Exogenous factors	Initial settings	
	Agent A	Agent B
Tc	0.9	0.9
Tp	0.9	0.9
Pp	0.9	0.9
Tn	0.1	0.1
Pe	0.1	0.1
Pk	0.9	0.1
El	0.9	0.1
Rn	0.9	0.1

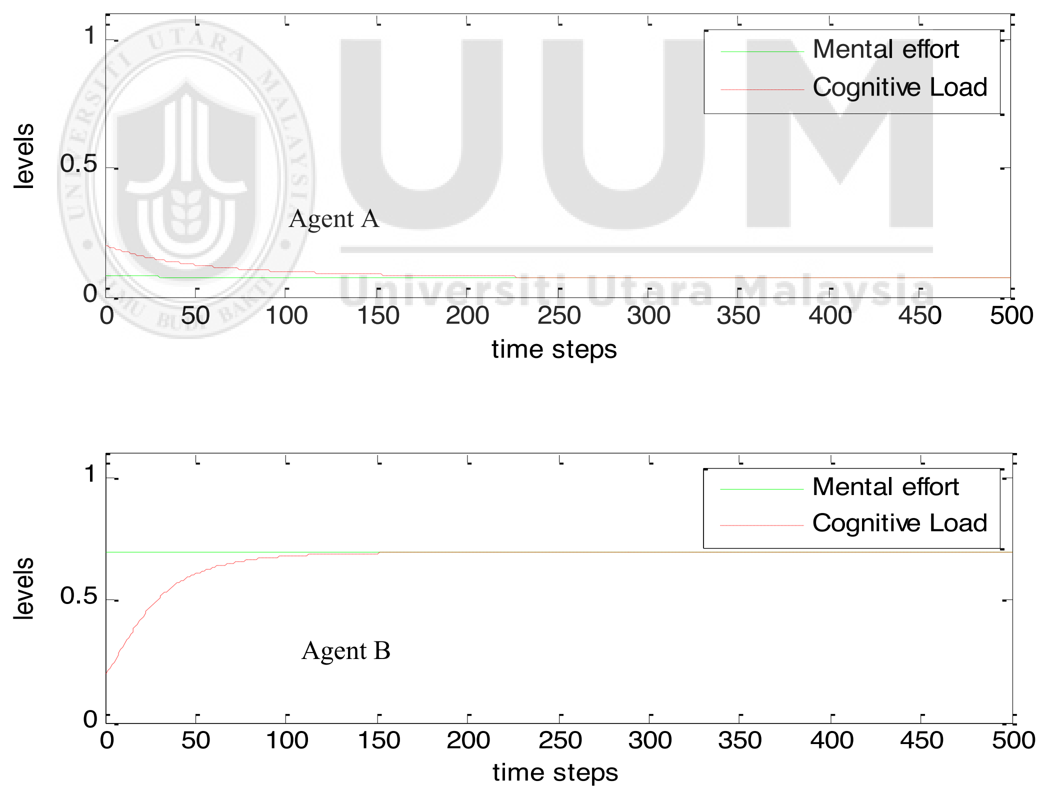


Simulation Results of Motivation and Persistence

b) Cognitive Load and Mental Effort

For simulating cognitive load and mental effort levels, simulation traces were generated based on different settings for two fictional agents as follows.

Exogenous factors	**Initial settings**	
	Agent A	**Agent B**
Tc	0.9	0.9
Tp	0.9	0.9
Pp	0.9	0.1
Tn	0.1	0.1
Pe	0.1	0.9
Pk	0.9	0.1
El	0.9	0.1
Rn	0.9	0.1

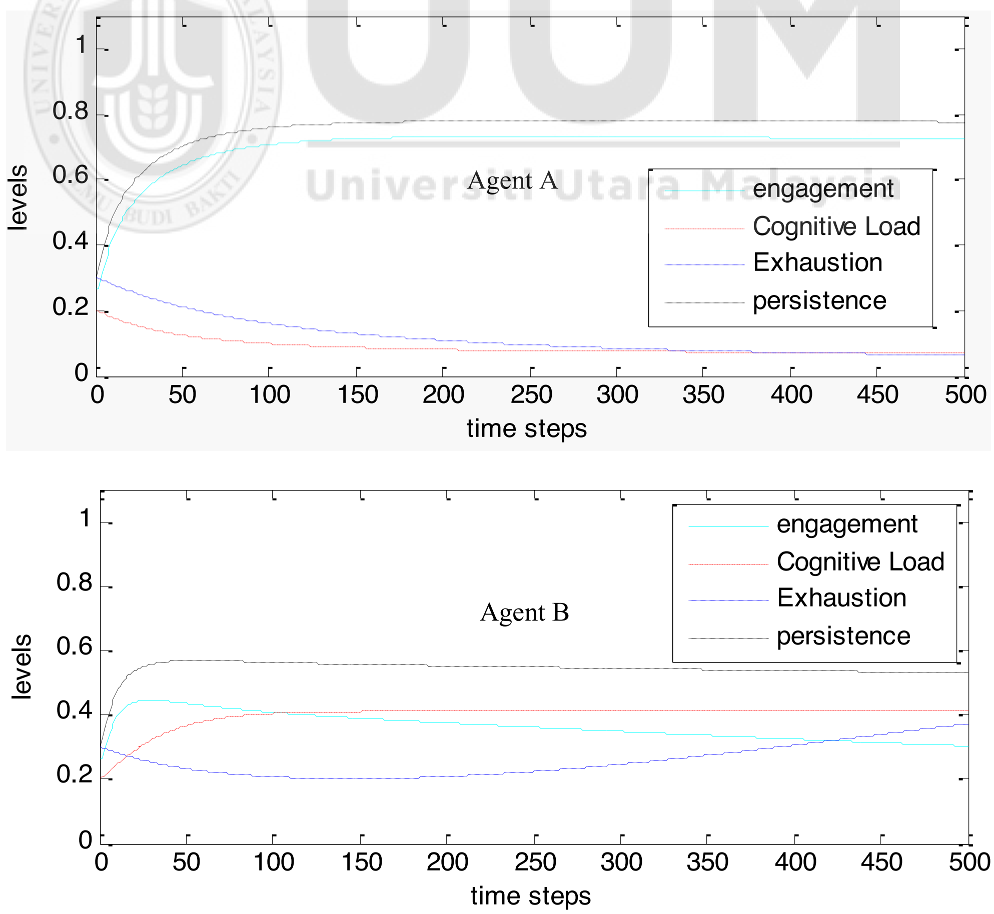


Simulation results of Cognitive Load and Mental Effort

c) Reader's Engagement

Engagement level during performing a reading task depends upon a persistence level. However, regardless of a reader being focused, a reader tends to disengage due to cognitive load and exhaustion effects. The results are depicted for two fictional agents as follows.

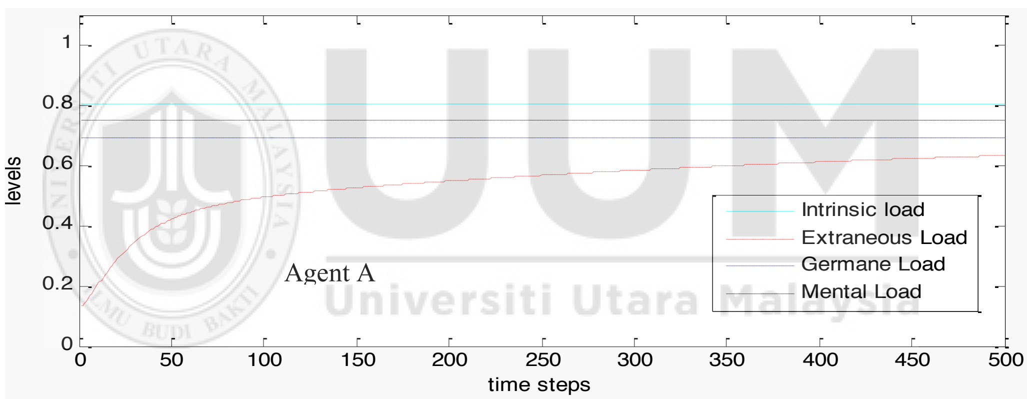
Exogenous factors	**Initial settings**	
	Agent A	**Agent B**
Tc	0.9	0.9
Tp	0.9	0.9
Pp	0.9	0.9
Tn	0.1	0.1
Pe	0.1	0.1
Pk	0.9	0.1
El	0.9	0.1
Rn	0.9	0.1

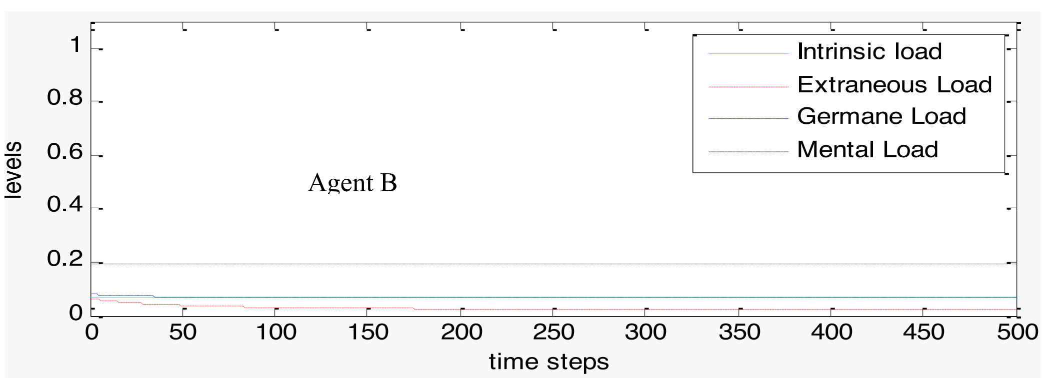


Simulation Results of Reading Engagement *d) Mental Load*

Mental load was computed as the weighted sum of intrinsic load, extraneous load, and germane load. Two fictional agents were simulated as follows.

Exogenous factors	Initial settings	
	Agent A	Agent B
Tc	0.9	0.9
Tp	0.9	0.9
Pp	0.1	0.9
Tn	0.1	0.1
Pe	0.9	0.1
Pk	0.1	0.9
El	0.1	0.9
Rn	0.1	0.9



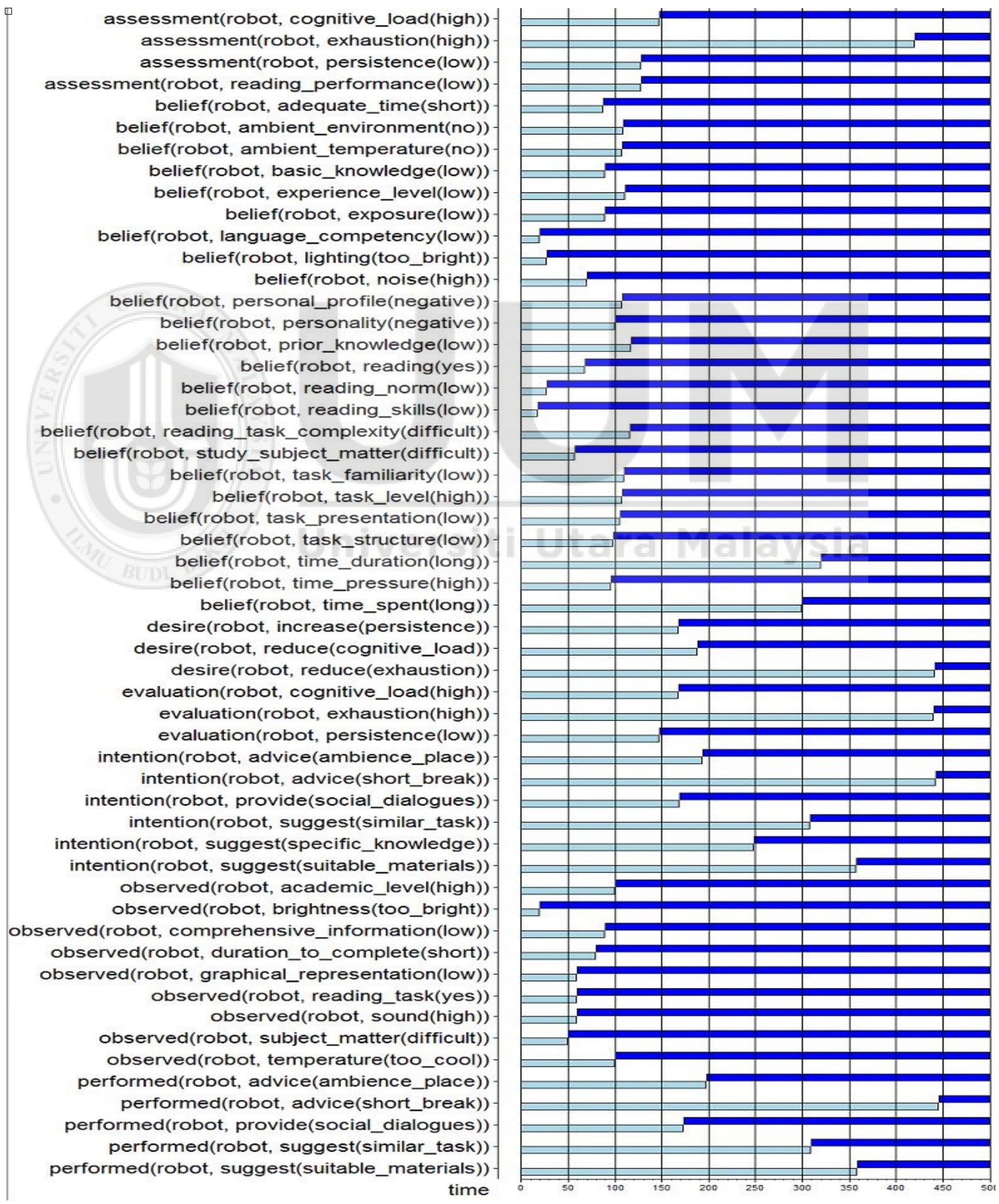


Simulation Results of Mental Load and Its precursors

2) Simulations for Ambient Agent Model

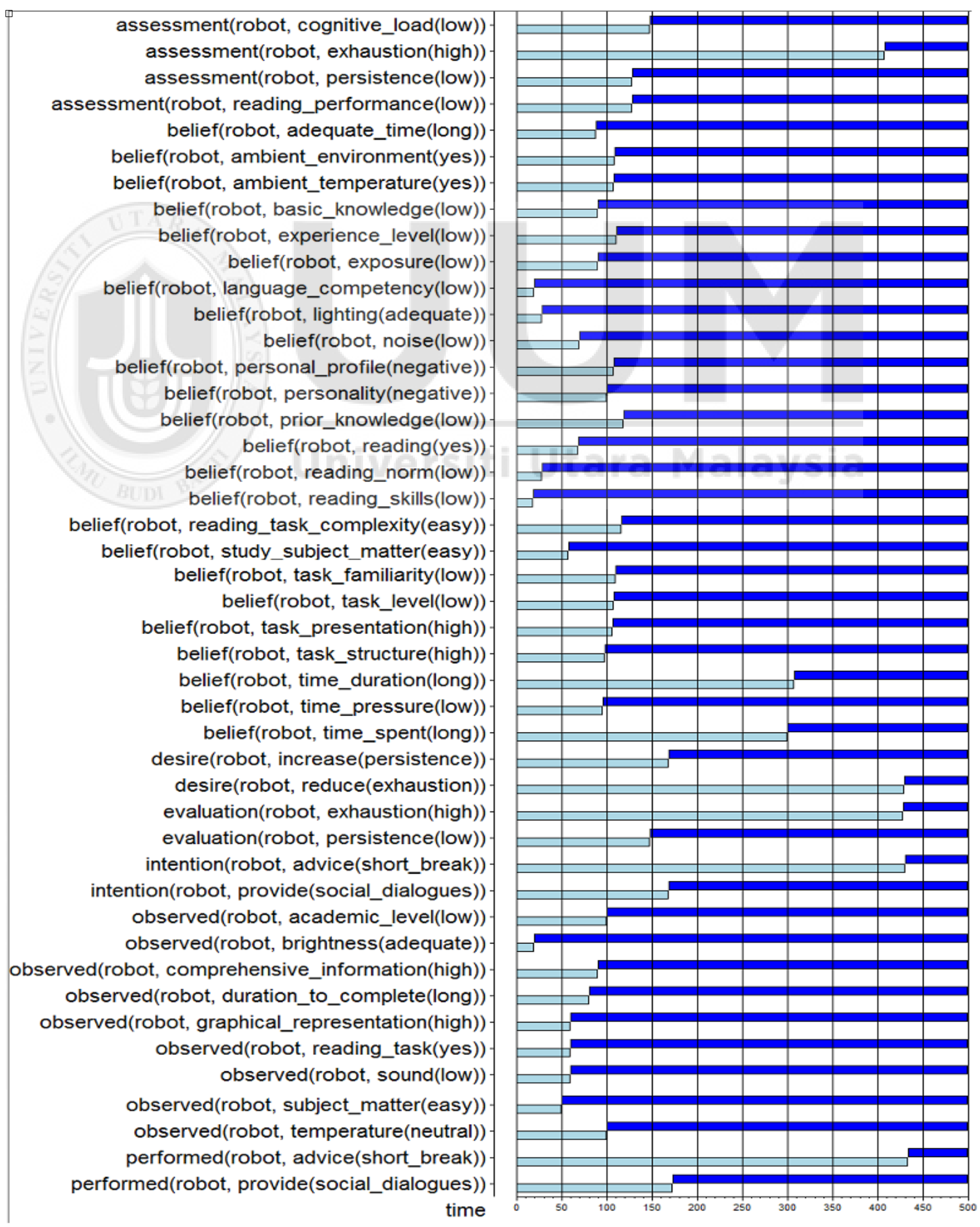
a) Demanding Task with Insufficient Reader's Resources.

In this simulation, the agent observes several conditions concerning reading task, such as; difficult subject meant for a higher academic level, distraction environment due to high level of sound, temperature, and brightness. Likewise, reading task is not presented with comprehensive and graphical information. A reader also has no enough knowledge and experience on the reading task. As a result, the agent will be able to assess reader's condition as time progresses and an appropriate action will be performed if all beliefs hold true. The detrimental conditions are high exhaustion, high cognitive load, low persistence, and low reading performance. The results are presented in the following figure.



b) Not Demanding Task with Insufficient Reader's Resources

If the agent observed that reading task has no impact on reader conditions where it was not difficult, meant for the right academic level, and presented with graphical and comprehensive information. The environment was not distraction as well. In addition, the agent believes that the reader is not skilled enough to perform the task. In this case, the agent will be able to assess three unwanted conditions through the time which are low persistence, high exhaustion, and low reading performance. With the time, the agent is able to tackle all the unwanted conditions as appropriate actions will be performed to each condition. The results are shown in the following figure.



Appendix F

Preliminary Study Questionnaire

Consent to participate in survey research of "Designing a sociable robot to support reading process"

You are asked to participate in a research study conducted by Hayder Mohammed Ali, doctoral candidate, Azizi Ab Aziz, *Ph.D.*, and Rahayu Ahmad, *Ph.D.*, from School of Computing at Universiti Utara Malaysia (UUM). The result of this survey will be used as apart in the doctoral thesis of Hayder Mohammed Ali. You were selected as a possible participant in this study because you have indicated that you are ready to provide identical feedback which is extremely appreciated in designing sociable robot. You should read the provided information below, and ask questions about anything you don't understand before proceeding to participate. Your participation in this research is completely unpaid and you are free to decide whether to be in it or not.

- **PURPOSE OF THE STUDY**

The purpose of this study is to acquire further information on major problems people might encounter during reading process and what types of technologies are to be incorporated in providing aid for them. Based on the result, a personal robot will be designed to support people during reading.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this survey and that can be identified with you will remain confidential and will be used only for research purpose.

- **IDENTIFICATION OF RESEARCHERS**

If you have any additional questions or concerns about this survey, please feel free and do not hesitate to contact:

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SECTION A: DEMOGRAPHIC DETAILS

Please mark (√) in the appropriate place provided.

1. Please indicate your gender?
☐ Male ☐ Female

2. Which of the following age categories do you belong to?
☐ <15 ☐ 15 - 20 ☐ 21- 30 ☐ 31- 40 ☐ > 41

3. Please identify your highest educational level?
☐ Ph.D. ☐ Master ☐ Diploma ☐ Undergraduate/ degree
☐ Matriculation/STPM/A level ☐ Others, Please state…………………

4. Please, specify your nationality**?**
☐ Malaysian ☐ Non- Malaysian, Please state……………………………..

5. Monthly earning/ pocket money in ringgit Malaysia (**RM/MYR**)

☐ < 1000 ☐ 1000 -2000 ☐ 2001- 3000 ☐ 3001- 4000 ☐ > 4000

6. Living situation

☐ Living alone ☐ Living with housemate ☐ Living with spouse
☐ Living with children ☐ Living with roommate ☐ Living with other relatives

SECTION B: PERSONALITY MEASUREMENT

Here are a number of characteristics that may or may not apply to you. For example, do you agree that you are someone who likes to spend time with others? Please write a number next to each statement to indicate the extent to which you agree or disagree with that statement

Disagree Strongly	Disagree a little	Neither agree nor disagree	Agree a little	Agree strongly
1	**2**	**3**	**4**	**5**

I see Myself as Someone Who...

___1. Is talkative
___2. Tends to find fault with others
___3. Does a thorough job
___4. Is depressed, blue
___5. Is original, comes up with new ideas
___6. Is reserved
___7. Is helpful and unselfish with others
___8. Can be somewhat careless
___9. Is relaxed, handles stress well
___10. Is curious about many different things
___11. Is full of energy
___12. Starts quarrels with others
___13. Is a reliable worker
___14. Can be tense
___15. Is ingenious, a deep thinker
___16. Generates a lot of enthusiasm
___17. Has a forgiving nature
___18. Tends to be disorganized
___19. Worries a lot
___20. Has an active imagination
___21. Tends to be quiet
___22. Is generally trusting
___23. Tends to be lazy
___24. Is emotionally stable, not easily upset
___25. Is inventive
___26. Has an assertive personality
___27. Can be cold and aloof
___28. Perseveres until the task is finished
___29. Can be moody
___30. Values artistic, aesthetic experiences
___31. Is sometimes shy, inhibited
___32. Is considerate and kind to almost everyone
___33. Does things efficiently
___34. Remains calm in tense situations
___35. Prefers work that is routine
___36. Is outgoing, sociable
___37. Is sometimes rude to others
___38. Makes plans and follows through with them
___39. Gets nervous easily
___40. Likes to reflect, play with ideas
___41. Has few artistic interests
___42. Likes to cooperate with others
___43. Is easily distracted
___44. Is sophisticated in art, music, or literature

Please check: Did you write a number in front of each statement?

SECTION C: READING HABITS

1. **Instructions**: Please circle the number that best represents your opinion to the following questions below

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

1.	Reading is very important in your daily life	1	2	3	4	5	6	7
2.	I prefer to read digital materials (screen-based)	1	2	3	4	5	6	7
3.	I prefer to read printed materials (Paper-based)	1	2	3	4	5	6	7
4.	Reading with your companions/ friends is better than reading alone	1	2	3	4	5	6	7

5.	It's easy for me to get distracted/ lose concentration during reading process	1	2	3	4	5	6	7
6.	Short rest/ pause after long duration of reading will help me to stay focus	1	2	3	4	5	6	7
7.	Reading for a very long duration causes me fatigue such as eye strain and backache.	1	2	3	4	5	6	7
8.	Reading for a very long duration causes me mental exhaustion such as lack of focus and tiredness	1	2	3	4	5	6	7

Please mark (√) in the appropriate place provided.

2. If you live with another person(s), do they support your efforts to read any materials?

☐ Yes
☐ No

If yes, please proceed with question 3

3. What kinds of support do they normally provide to you? **(***You can choose more than one***)**

☐ Encouraging words to keep you reading
☐ Sharing conversations about what you are reading
☐ Provide refreshments to you
☐ Don't make noise to let you focus
☐ Others, please state………………………………………………

4. Do you have a person(s) who will support you when you are reading something?

☐ Yes
☐ No

If yes, please proceed with question 5

5. What kinds of support do they normally provide to you? **(***You can choose more than one***)**

☐ Encouraging words to keep me reading
☐ Sharing conversations about what you are reading
☐ Provide refreshments to me
☐ Don't make noise to let me focus
☐ Others please state……………………………………………………..

6. What type of reading techniques do you most apply during reading? (*you can choose more than one)*

☐ Skimming (*confirm the general idea of the text*)
☐ Scanning (*seeking for specific piece of information*)
☐ Close reading (*paying very close attention / complete searching*)

7. What type of reading materials you usually prefer to read during reading process? (You *can choose more than one*)

☐ Newspapers
☐ Magazines
☐ Novel/ Story book
☐ Textbook/ Journal
☐ Comics
☐ Websites
☐ Others, please state……………………………………………

8. Where do you normally read? (*you can choose more than one*)

☐ At the library
☐ At the table

- ☐ At school
- ☐ At other homes
- ☐ On the bed
- ☐ In the living room
- ☐ In front of the TV or computer
- ☐ Public place (*e.g. airport, bus/train station*)
- ☐ Coffee shop/ Restaurant
- ☐ Anywhere I can
- ☐ Others, please state……………………………………..

9. When you read, how much time do you spend reading?

- ☐ About 15 minutes
- ☐ About half an hour
- ☐ About an hour
- ☐ More than an hour

10. How often do you read something?

- ☐ 1-2 times a week
- ☐ 2-3 times a week
- ☐ 4-5 times a week
- ☐ Every day
- ☐ Others, please state……………………………………………..

11. If you are losing concentration during reading, what are the reasons do you think that cause the problem? (*You can choose more than one*)

- ☐ Drowsiness
- ☐ Prior commitment (*e.g. appointment, scheduled activities*)
- ☐ Difficult to understand
- ☐ Tiredness
- ☐ Noise
- ☐ Bored
- ☐ Stress
- ☐ Hungry
- ☐ Others, please state …………………………………………….

12. If you are given a digital device for reading, what device will you use during reading process? (*you can choose more than one*)

- ☐ E-book readers (*e.g. Amazon kindle*)
- ☐ Tablet
- ☐ Desktop
- ☐ Laptop
- ☐ Smart phone
- ☐ Others, please state ……………………………………………..

13. What make you prefer digital devices during reading process (*you can choose more than one)*

- ☐ Zoom in and Zoom out
- ☐ Highlighting particular text
- ☐ Easy to copy and paste
- ☐ Very fast in searching
- ☐ Multimedia (*interactive*)
- ☐ Portability
- ☐ Annotation (*make notes*)
- ☐ Others, please state………………………………………

SECTION D: PERSONAL ROBOTS

Introduction: Personal robots are robotic technologies that have been developed to engage/ interact with people and also to partake in people's daily lives in rich and rewarding ways to help them live healthier lives, connect with others and learn well.

Please mark (√) in the appropriate place provided.

1. Based on the photos above, what image of personal robots do you have?

☐ Good (It is good for helping human)
☐ Bad (It constitutes danger and replaces man)
☐ Neutral (It depends on what is done with it)

2. Do you have any personal experiences with personal robots?

☐ Yes
☐ No
☐ Uncertain

3. How do you prefer the embodiment/presentation of your personal robot?

☐ Physical embodiment
☐ Virtual embodiment (on the screen/ avatar)
☐ Uncertain

4. How do you prefer your personal robot to look like?

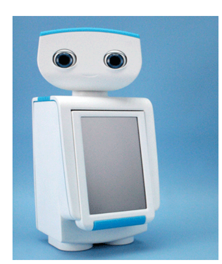
☐ Human-like
☐ Machine- like
☐ Animal- like
☐ Uncertain

Vignette:

AUTOM is a personal robot (coach robot for weight loss) that has been developed to professionally interact/ engage with people to keep track their losing weight progress. It became an integral part in their daily lives.

Some of Autom's features:

1. It possesses expressive, blue eyes that even offer up the occasional wink
2. It is able to motivate its users to continue their diet program
3. It is able to remind its users to eat healthy
4. It has short conversation to communicate with its users
   (No two conversations are alike)
5. It is able to adapt with its users' needs and daily activities



AUTOM

5. Based on the concepts above, please circle the number that best represents your opinion about designing a personal robot that can help you during reading?

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

1.	I like the idea of having a personal robot that can support me during reading	1	2	3	4	5	6	7
2.	I can afford to have a personal robot at home	1	2	3	4	5	6	7
3.	Personal robot can encourage/motivate me during reading	1	2	3	4	5	6	7
4.	Personal robot can help me to reduce my fatigue such as backache and eye strain during reading	1	2	3	4	5	6	7
5.	Personal robot can help me to reduce my mental exhaustion such lack of focus and tiredness during reading	1	2	3	4	5	6	7

6. If one of these objects will be represented as a personal robot to assist your reading process, kindly, circle the priority for each object**?**

1. Table lamp	LOWEST PRIORITY	1	2	3	4	5	HIGHEST PRIORITY
2. Mug/ Cup	LOWEST PRIORITY	1	2	3	4	5	HIGHEST PRIORITY
3. Pen holder	LOWEST PRIORITY	1	2	3	4	5	HIGHEST PRIORITY
4. Table fan	LOWEST PRIORITY	1	2	3	4	5	HIGHEST PRIORITY
5. Clock	LOWEST PRIORITY	1	2	3	4	5	HIGHEST PRIORITY

Please check: No two objects can have the same priority.

7. If there is a personal robot to assist/ accompany you during reading, what is the function the robot should do? (*You can choose more than one*)

- ☐ Remind me to take a break
- ☐ To control the intensity of light
- ☐ Motivate me for reading
- ☐ Play music
- ☐ Short conversation
- ☐ Others, please state what other functions you might think that robot should do?

8. What are the qualities you prefer to be added to the personal robot that can assist you during reading? (*You can choose more than one*)

- ☐ Intelligence (*the capacity for knowing your needs*)
- ☐ Empathy (*the capacity for recognizing your feeling*)
- ☐ Rationality (*the capacity for reasoning and respond logically towards you)*
- ☐ Reliability *(the capacity of robot to be trusted by you)*
- ☐ Others, Please state ……………………………………………..

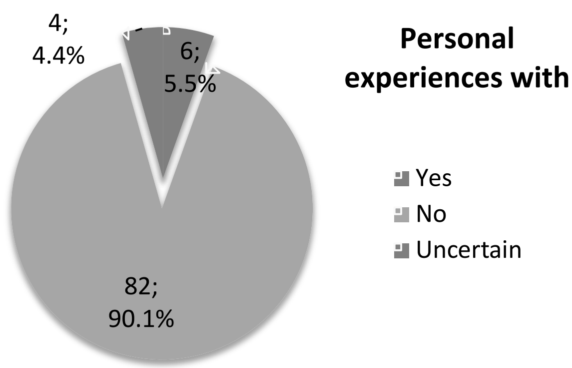
Appendix G

Survey Results

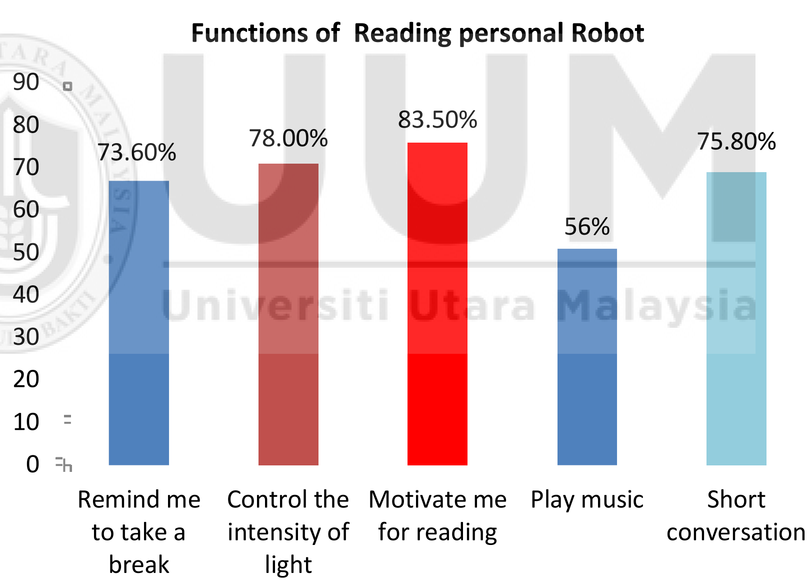
Overview of Demographic Information

	Frequency	Valid %
Respondent's Gender		
Male	44	48.4
Female	47	51.6
Total	91	100.0
Respondent's Age		
15 – 20	4	4.4
21- 30	69	75.8
31- 40	11	12.1
> 40	7	7.7
Total	91	100.0
Respondent's Living situation		
Living alone	17	18.7
Living with housemate	2	2.2
Living with spouse	7	7.7
Living with children	2	2.2
Living with roommate	57	62.6
Living with other relatives	6	6.6
Total	91	100.0
Respondent's Monthly income		
< 1000	53	58.2
1000 -2000	16	17.6
2001- 3000	15	16.5
3001- 4000	3	3.3
> 4000	4	4.4
Total	91	100.0
Respondent's level of education		
Ph.D.	10	11.0
Master	39	42.9
Diploma	1	1.1
Undergraduate/ degree	33	36.3
Matriculation/STPM/A level	8	8.8
Total	91	100.0
Respondent's Nationality		
Malaysian	62	68.1
Non- Malaysian	29	31.9
Total	91	100.0

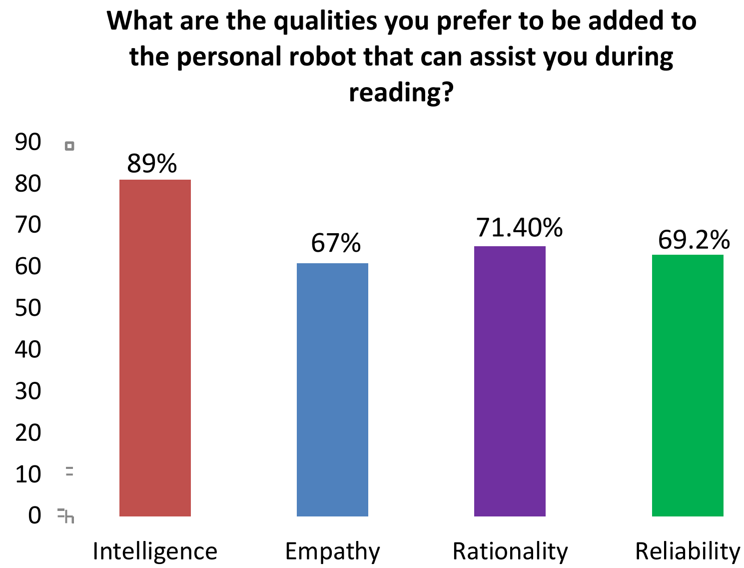
- Readers' personal experiences towards using personal robots were surveyed and revealed that 90.1 percent of the respondents got no experiences with robot.



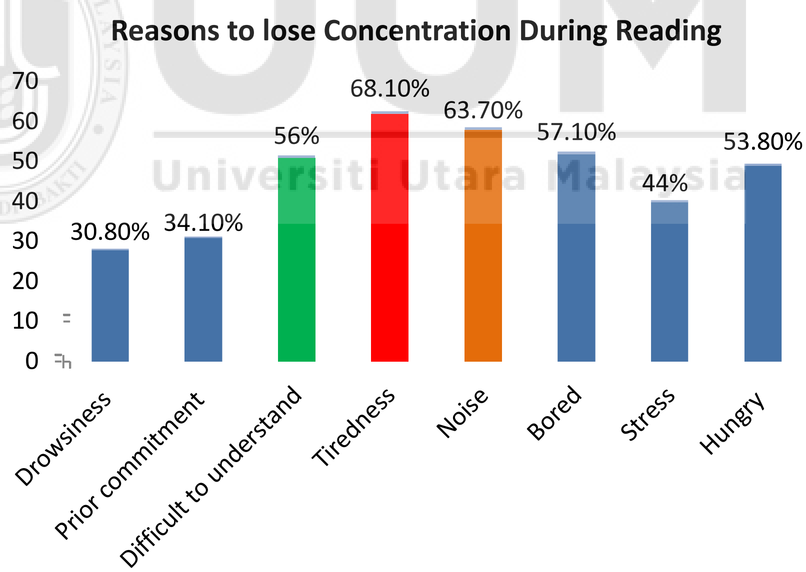
- Apart from determining what object is preferred to be represented as a robot, readers determined what functions they wish the robot has and the result is as follows:



- Respondents specified the qualities they wish the robot should have. Respondents prefer the robot to have some qualities such as *intelligence* (the capacity for knowing your needs), *empathy* (the capacity for recognizing your feeling), *rationality* (the capacity for reasoning and respond logically towards you), and *reliability* (the capacity of robot to be trusted by you). The result is shown as follows.



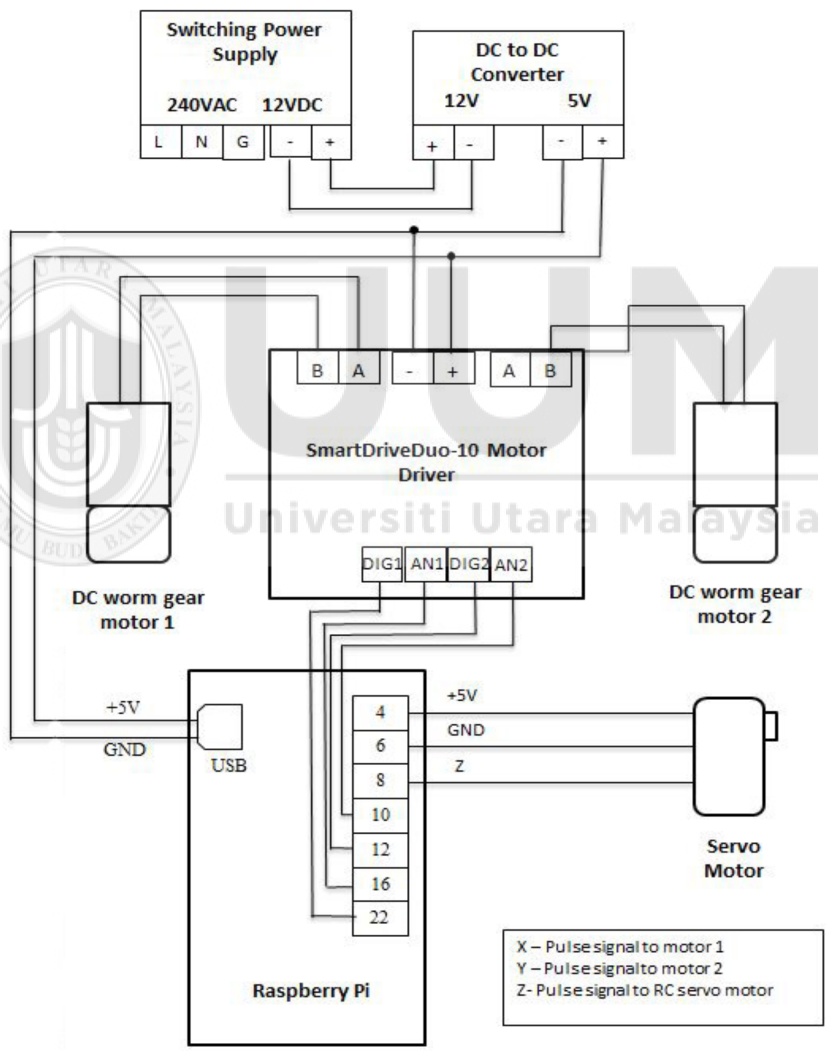
- Respondents were highlighted the reasons that have major impacts on reading. The results were shown as follows.



Appendix H
Hardware Components Specifications

- **Electronic Circuit Design**

The electronic circuit diagram for all the hardware components was made. This circuit visualized how robot's electronic components can be powered from any typical power source with 220/240V AC using a switching power supply and a DC- to- DC converter.



Electronic Circuit Diagram for IQRA'

First, the switching power supply converts 240V (AC current) to 12V (DC current). Next, the 12VDC-to-5VDC converter is used to power the Raspberry Pi and the motor driver (SmartDriveDuo-10) with 5V. Furthermore, Raspberry Pi powers the servo motor (using General-Purpose Input/Output (GPIO) pin 4 / GPIO4) while the motor driver powers the other two DC motors. It is interesting to mention that the Raspberry Pi microprocessor controls the direction (Cartesian coordinates) of the DC motors (DIG1 and DIG2) using GPIO12 and GPIO22 by sending analogue signals (AN1 and AN2) via GPIO10 and GPIO16. Also, it controls the servo direction by sending a PWM (Pulse Width Modulation) signal using GPIO8.

- **Physical Driver Components**

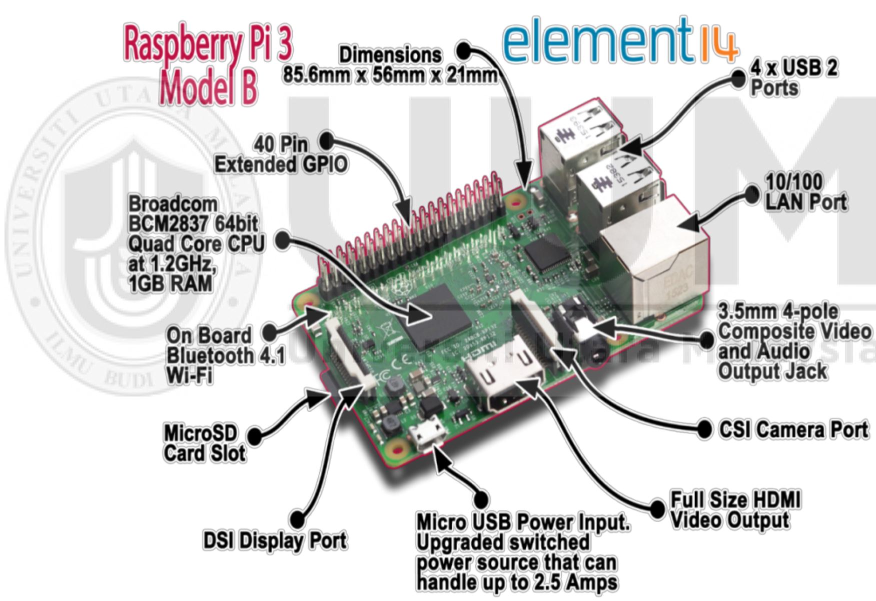
IQRA' was designed to support four-degrees-of freedom (4DOF). The first 2-DOF allows the robot head to rotate from left to right directions (within 55 to 130 degrees). Another 2-DOF permits the entire body (robot's arms) to move forward and backward direction (to allow changes in social space interaction within the range of 0-30 degrees). Although the maximum rotational degrees of servo motors are between 0-180 degrees, the 55 to 130 degrees range have been chosen as the results from extensive experiments to determine the optimal positions for the robotic head. Moreover, it is more realistic to mimic a maximum rotational position of a human neck as a basis for subtle social human-robot interaction to take place. In addition to the motors movements, the interface of the robot (the head-mounted Android mobile phone) has an interactive animated character to give a sense of a living and sociable object (animacy).

- **Robot Microcontrollers**

This section explains the essential micro-electronic devices that are used to construct IQRA'. There are three different devices, namely; Raspberry Pi, Android mobile phone, and Smart Motor Drive were used to control the entire behaviours of the robot. The detailed descriptions of these devices are explained as follows.

I. Raspberry Pi

The huge advancement in electronic devices make it easily for developers to get palm size and low-cost electronic boards, like Raspberry Pi microcontroller that carry extraordinary capabilities like a normal personal computer processor. The figure below shows the Raspberry Pi design and its physical components. Due to its versatility and costs, Raspberry Pi is selected as a platform to control the movement of the robot. IQRA' utilizes the Raspberry Pi 3 Model B -version 1.2 as a microcontroller platform and was purchased online via https://www.element14.com website.

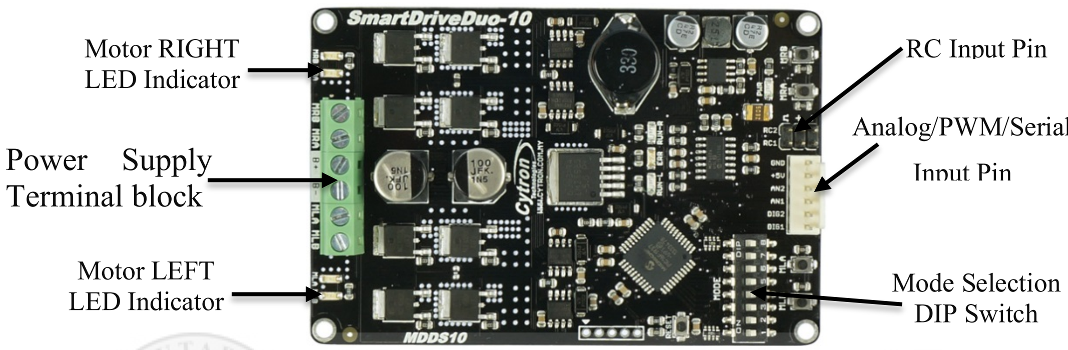


Physical Components of Raspberry Pi (from https://www.element1 4.com website)

The detailed explanations of Raspberry Pi variants and its capabilities can be obtained in Upton and Halfacree (2014).

II. SmartDriveDuo10

As Raspberry Pi is limited only to handle up to 5V, and any overloading current can cause damage or burn itself, the smart motor driver dual channels is needed to allow extra voltage for certain drivers. In this study, the SmartDriveDuo10 is preferred as an additional device to power robot's DC motors. This component is designed to drive a medium power brushed DC motor with a maximum current capacity up to 30A peak (few seconds) and 10A continuously. Primarily, this driver is designed specially to control a differential-drive mobile robot. The following figure depicts the SmartDriveDuo10 motor driver.



Motor Driver SmartDriveDuo10 (from https://www.cytron.io website)

This motor driver was purchased online from https://www.cytron.io. The detailed specifications (including user manual) for SmartDriveDuo10 motor driver can be found from the mentioned website.

III. Android Phone

The Android-based smartphone was chosen to serve as a robotic face and its main computational unit due to the versatility and robustness to process real time data from Raspberry Pi microcontroller. Moreover, this decision was made due to its popularity, low developmental cost, open source platform and its rich hardware and Java platform support. In fact, an Android platform requires low development costs due to no licensing fees or expensive development tools are needed. Given the extensive set of Java libraries supported by Android OS and its comprehensive Software Development Kit (SDK), it facilitates any Java developers to create or extend the application even with a little bit Android experiences.

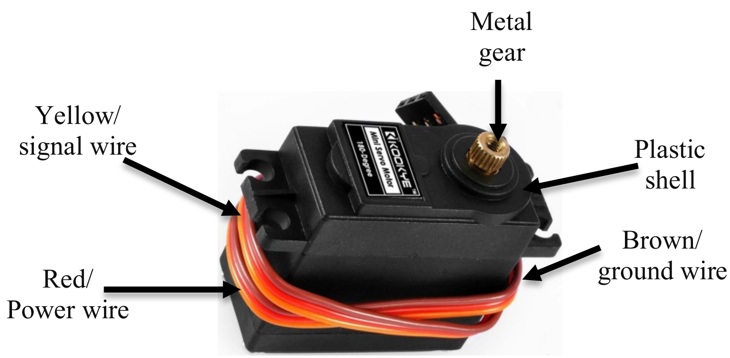
Once an Android OS based smartphone is chosen, the next step is to select the model in implementing the robotic tasks. For this purpose, a model name ASUS ME172 V 4.1.1 is selected due to the screen size, weight, and its resolution to display vibrant animations. This ability is needed to transform the phone into a believable mediated friendly character.

ASUS ME172V 4.1.1

Besides that, the ASUS phone is reasonable choice due to its lightweight design and maximum load of the motor carrying capacity for stall torque conditions.

- **Servo and DC Motors**

Within robotic hardware components, both servo and DC motors are considered as the main components for the robotic development. For example, the servo motor is used to manipulate the robot head movement for realistic and subtle human-robot interactions. Therefore, to fulfil this requirement, a high torque RC servo motor with straight mounting that capable to perform 180 degrees rotation is chosen. The key reason to use this servo motor for IQRA' is because of it is affordable, capable to support high torque, and can be communicated with the Raspberry Pi microcontroller. The selected servo motor that controls left/right movement of IQRA' robotic head is depicted as follows.



Similarly, two DC "Dual shaft self-locking DC worm gear motor" motors powered by Raspberry Pi are used to control the physical robot movement during the interaction. The figure below shows the type of a DC motor that was used in the robot's construction process.

Robot's DC Motor

- **Technical specifications** for both servo and DC motors as well as circuitry design related to the switching power supply, and DC- to- DC converter are detailed out as follows.

SmartDriveDuo-10 Motor Driver Specifications:

- Input Voltage (Motor): 7 - 35VDC
- Single power operation
- Dual Channels, means it can drive two brushes motor independently, or mixed.
- Operating modes: RC (RC servo signal), Analog, PWM, simplified and packetized UART.
- Two manual/test buttons for each channel.
- Two output indicator LEDs for each channel.

Dual shaft self-locking DC worm gear motor Specifications:

- Rated Voltage: 12V.
- No load speed: 16 RPM
- Power Supply: Regulated DC power supply

High Torque RC Servo Motor with Straight Mounting

- Max rotating angle: 180°
- Operating torque: 15Kg.cm at 6.0V; 16Kg.cm at 7.4V
- Operating speed: 0.16sec/60° at 6v; 0.14sec/60°at7.4v
- Idle running current: <500m

Switching Power Supply 240V to 12V

- Size: 15.8 x 9.7 x 4.2cm
- Input Voltage: 100~120V AC, 200~240V AC (Preset 220V)
- Output Voltage: 12V DC
- Output Current: 0~10.0A
- Shell Material: Metal case / Aluminum base
- Protection: Shortage Protection, Overload Protection, Over Voltage Protection

DC to DC Converter

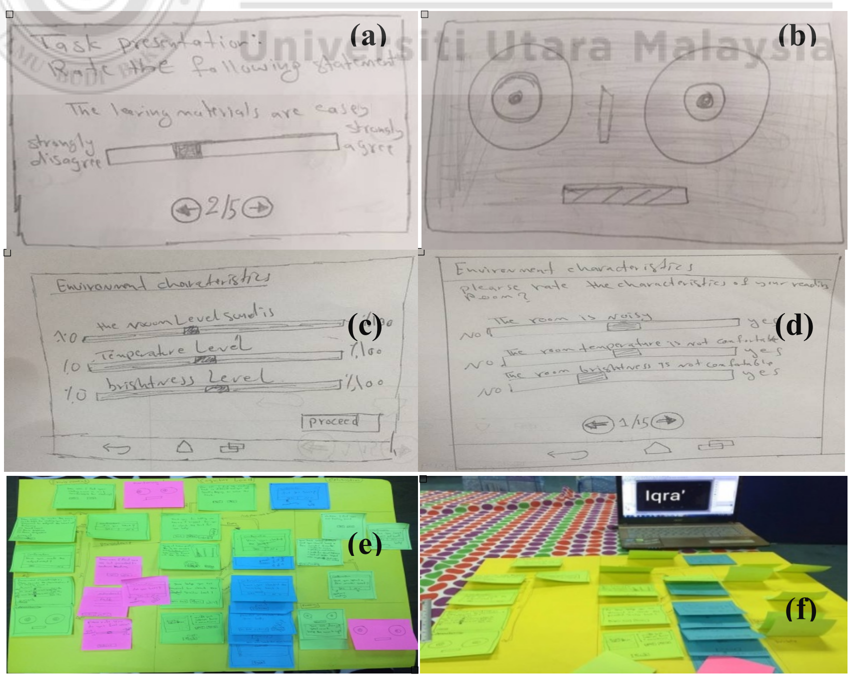
- Input: DC 8-20V, (12V changes to 5V)
- Output: DC 5V, 3A, 15W.
- Size: 46mm X 27mm X 14mm.
- Synchronous rectification, the conversion rate is ≥96%, very low heat.
- With overload/over-current/over temperature/short circuit protection and it can work in normal condition when restored.
- All epoxy sealed containers with Waterproof Housing.
- Compact design, high efficiency, easy installation and use.

Appendix I

Low and High-Fidelity Prototypes

Low-Fidelity Prototype (Lo-Fi)

Basically, the low fidelity (paper prototyping) provides a limited functionality and restricted amount of interaction. It helps to generate various design alternatives for fast and crude prototype development manners to demonstrate the basic system functionalities. In other words, it visualizes the fundamental design ideas at the beginning of the design process. The outcome from this process is a conceptual prototype which is simple, cost saving, and fast (Sefelin, Tscheligi, & Giller, 2003). In this study, all the system interfaces were sketched on papers to get better understanding and design alternatives prior to the real working prototype deployment. Following figure shows some results from the Lo-Fi prototyping stage.

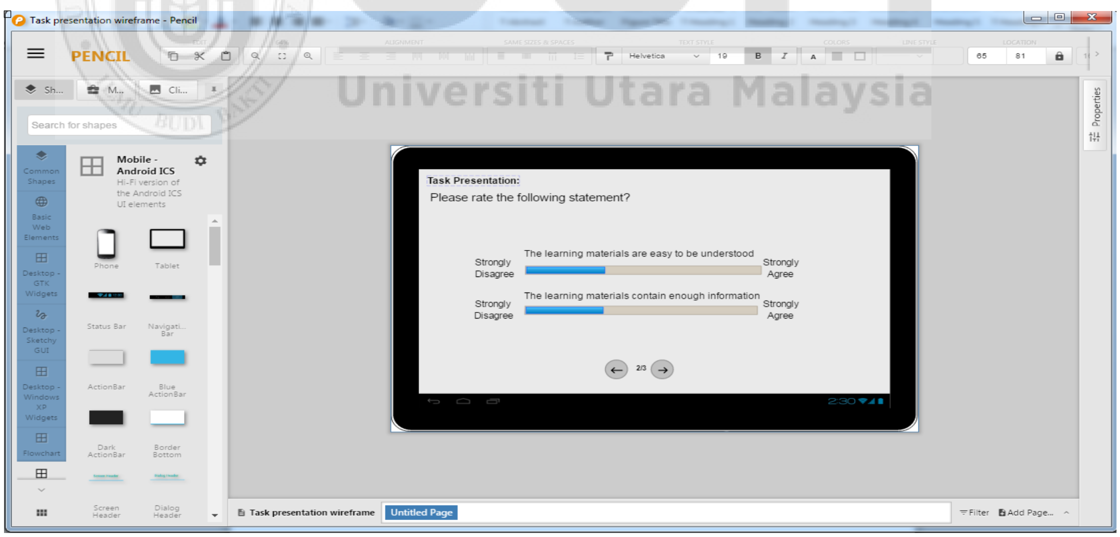


Low Fidelity Prototypes

The examples of the paper-based prototyping design (Lo-Fi) related to the robotic interfaces are; a) the animated face of the robot in (b), and the slider bar designs for the input processes (a, c, and d). Correspondingly, the whole Lo-Fi results for the human-robot interfaces are shown in (e) and (f). Next, all the obtained conceptual designs from this this stage provide an underlying construct for software developmental process (High-Fidelity prototyping) as described in the next section.

High-Fidelity Prototype (Hi-Fi)

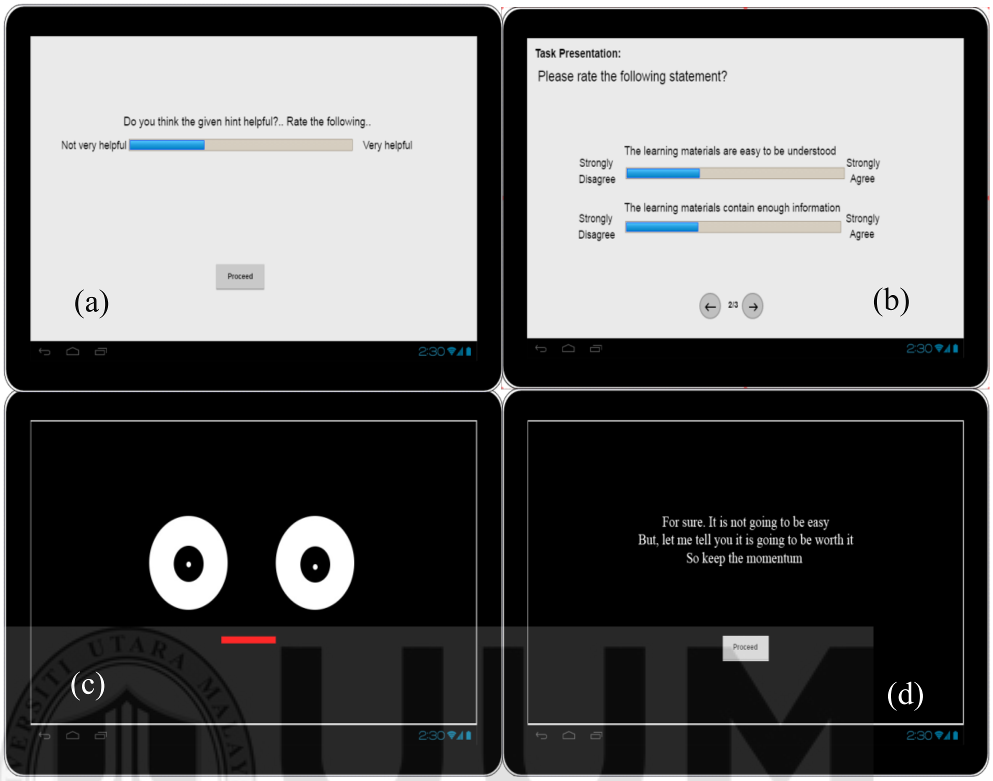
The High- Fidelity prototype (high fidelity wireframe) aims to visualize the final design of the user interface with all system functionalities. The Hi-Fi prototype has a higher degree of realism and it is always considered identical to the final product (Walker et al., 2002; Tsai & Yang, 2017). Moreover, the Hi-Fi prototype enables application developers to test entire system (e.g., the flow of the system) prior to the real /final development stage.



Pencil Developmental Platform Software

As such, once the Lo-Fi prototype for the robot interfaces has been completed, the Hi-Fi prototype is developed by using an open-source wireframe tool called Pencil.

Consequently, a few examples from the high-fidelity stage are depicted as follows.



High Fidelity Prototypes

The figure shows the Hi-Fi design output of a slider bar to capture user's confirmation for provided support (as in a), and user's inputs for robot's computational derived beliefs about the task presentation (as in (b)). Also, both screenshots in (c) and (d) depict the robotic believable interface and motivational spoken text on screen respectively.

Appendix J

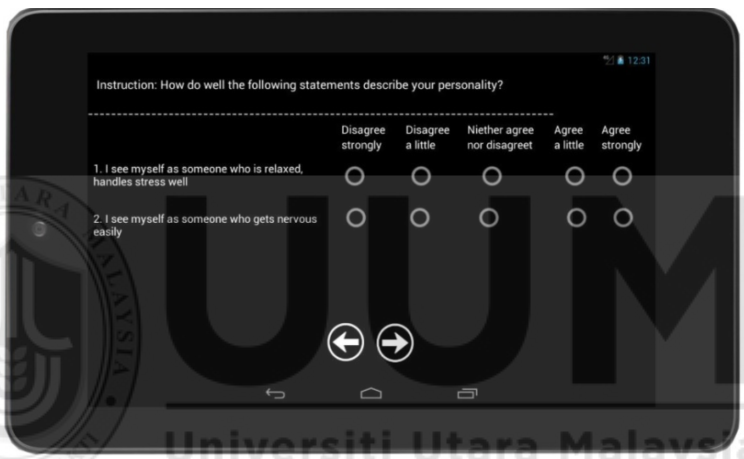
Robot User Interface

Robot's Observation Interfaces:

Initially, the reading companion robot collects individual data (data acquisition). Towards this end, the robot will show different screens asking the users to answer several questions related to its observation. Next, users will key-in their answers using enabled touch slider where the user has to select the slider based on a range between 0 and 100. The followings are examples of the robot interfaces for data acquisition.

Robot Data acquisition

Furthermore, the personality of the user was collected following the Big-Five inventory where two questions were used to measure neuroticism. Not here, personality in this work refers to general concept of positive or negative personality where neurotic person was determined as a person with negative personality (represented as 0) while a person with any of the other four personalities (openness, extroversion, introversion, conscientiousness) was determined with positive personality (represented as 1). As such, the interface to measure the personality of the reader was as follows:



The value from the interface was calculated as follows. First, the answer from the question one was reversed as explained in the descriptions of Big Five Inventory scoring (i.e., if a reader selected *agree strongly* which represents 5, then the value must be reversed to be 1 and vice versa). Later, the following formula was used to measure the derived belief for personal profile.

$Normalize\_Q_j = N_i / N_{maxi}$

$Neu\_score = \sum Normalize\_Q_j / 2$ Then,

$Personal\_profile = 1 - Neu\_score$

For example, if a reader's answers for question one is *disagree strongly* (1) and for question two is a*gree strongly* (5), the personal profile value was computed as follows:

Reverse ***Disagree strongly*** to 5. Then,

$Normalize\_Q_1 = 5/5 = 1$ And,

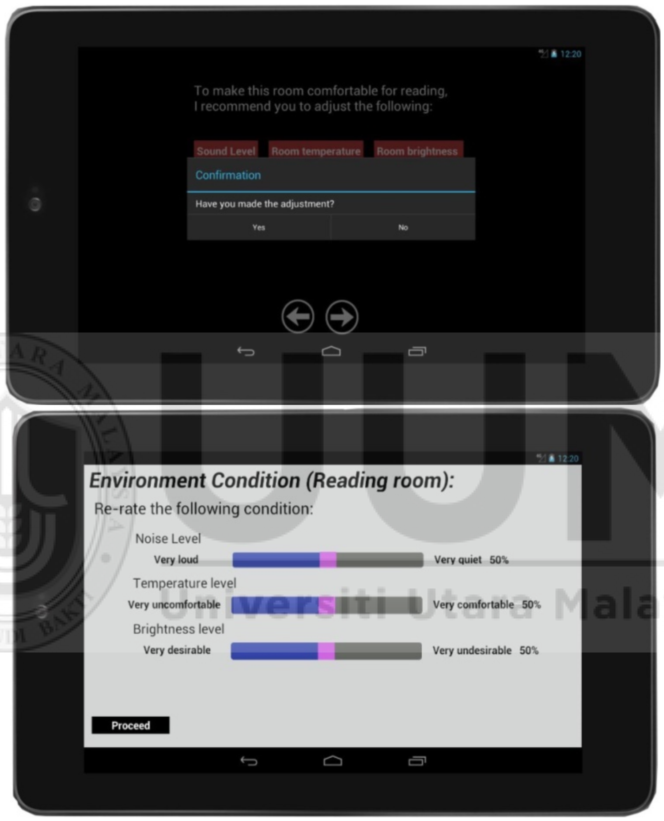
Normalize_Q$_2$=5/5=1

Neu_score=1+1/2=1, this leads to:

Personal_profile= 1-1= 0,

It means the personality of the reader is negative.

Robot's Discrepancy Evaluation Interface



A screen showing spoken evaluation dialogue printed to screen

Robot's supports actions Interface