An Agent-Based Model for Refined Cognitive Load and Reading Performance in Reading Companion Robot

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***Abstract*—This paper presents the importance of modeling dynamical behaviors of human cognitive states that serves as a core foundation in creating intelligent and responsive systems. It discusses in detail the development of a dynamical model of cognitive load and reading performance which acts as the central component of creating a reading companion robot. Simulations results show realistic behaviour patterns that adhere to the literature. Finally, the results produced from an automated verification approach to validate the internal correctness of the proposed model using Temporal Trace Language (TTL) are shown.**

***Index Terms*—Agent-Based Modeling; Dynamic Behaviour; Reading Performance; Simulation; Software Agent.**

I. INTRODUCTION

In recent years, the advancement in developing intelligent systems that is capable of providing personal cares to human has increased exponentially. The notable power of such systems is the ability to analyse human conditions and proactively support them to improve quality of life and facilitate daily activities. The idea of having such applications depends substantially on the availability of adequate knowledge for analyzing information on human functioning. In other words, human-functioning models are becoming vital elements to creating new intelligent applications [1]. The models provide the applications with the ability to reason and perform humanlike understanding and based on this understanding, personalized supports will be given by undertaking actions in some knowledgeable manner that influence the human's wellbeing and performance [2, 3].

Thus, as an initial phase to develop an intelligent application (i.e., table lamp robot) that helps readers when they are experiencing cognitive overload and exhaustion, we have earlier developed a dynamical model of cognitive load and reading performance and details of the model are presented in [4]. However, the previous model did not integrate some aspects that are crucial towards the development of a software agent model. Thus, due to its limitation and recent findings obtained from the literature, several refinements have been made to the previous model.

Pertaining to the aforementioned explanation, this paper discusses the generic process of creating a functioning model of cognitive load and reading performance in the software design of a reading companion robot. The outlines of this paper is organized as follows; Section II explains the generic idea on the development processes of a reading companion robot and how the dynamic model of cognitive load and reading performance can be used as the core component. Besides, it shows the global factors of the dynamic model. In Section III, the internal specifications and relationships to explain the development of the model are presented. Next, simulation results of the model are shown in Section IV. The model is logically analyzed and results are shown in Section V. Finally, Section VI concludes the paper and describes future work.

II. GLOBAL COMPONENTS

To acquire more details on users' preferences and interests for our proposed idea (a reading companion robot), we have conducted a pilot study and requirements analysis (refer to [5]). The study has shown that a table lamp is the most preferred object / medium to be represented as a personalized reading companion robot when people read their books. Because of this, efforts have been made to develop a software and assemble hardware components for the robot. Figure 1 visualizes the representation of our proposed robot.

Figure 1: The Pictorial Idea of a Table Lamp Robot

With respect to the software design, several different components are integrated to construct the robot's reasoning ability. These components are: 1) cognitive analytic that represents the dynamic model of cognitive load and reading performance, 2) analysis algorithm to perform reasoning using observational information about reader and the cognitive model, and finally 3) support module is to generate support actions. Figure 2 illustrates how the dynamical model of cognitive load and reading performance is used as a cognitive analytical tool to understand the dynamic behavior of a reader during reading task. This paper focuses on the refined model of cognitive load and reading performance while the software and hardware components are left out.

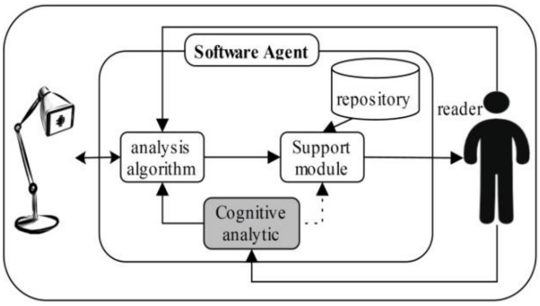

Figure 2: Software Agent Modules

In our work, the network oriented modeling approach based on temporal causal network is used to develop the dynamical model of cognitive load and reading performance [6]. In this model, four main different components incorporated to construct the model are: i) load, ii) exhaustion, iii) persistence, and iv) performance. Figure 3 shows the composition of the model at the highest level of abstraction.

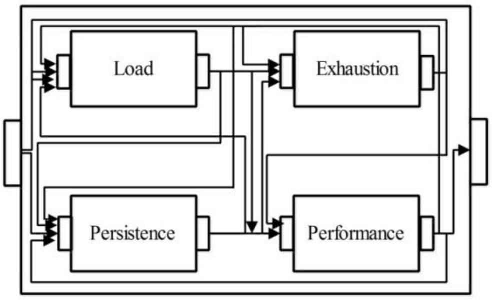

Figure 3: The Composition Model of Cognitive Load and Reading Performance

As in Figure 3, the cognitive model will receive information about a reader based on the exogenous factors as mentioned in next Section. Later, information will be exchanged among the internal processes to generate the global impacts of the four components. Note here, no change has been made to the four main states in the previous model. However, the revision happened mainly in the dynamic of the internal processes of Load state based on the recent found literature on Cognitive Load Theory [7]. More explanations are presented in the next section of this paper.

III. THE FORMAL MODEL

A dynamical model of cognitive load and reading performance is refined to be more reasonable and in line with Cognitive Load Theory (CLT) [8]. In addition, the cognitive processes of the model and its states have been re-connected and re-formalized to eliminate the unnecessary factor such as *learning occurrence* as the model was developed to understand the temporal effects of *persistence*, *cognitive load*, *exhaustion*, and *reading performance*(i.e., in terms of engagement). Figure 4 shows the refined conceptual model of cognitive load and reading performance. The decomposition process of the model results several different factors based on their relationships, namely; 1) *exogenous*, 2) *instantaneous*, and 3) *temporal relationships*. All the exogenous, instantaneous and temporal factors of the model with their formal notations have been summarized in Table 1. Further theoretical explanations about the model's factors can be found in our previous works [4, 9].

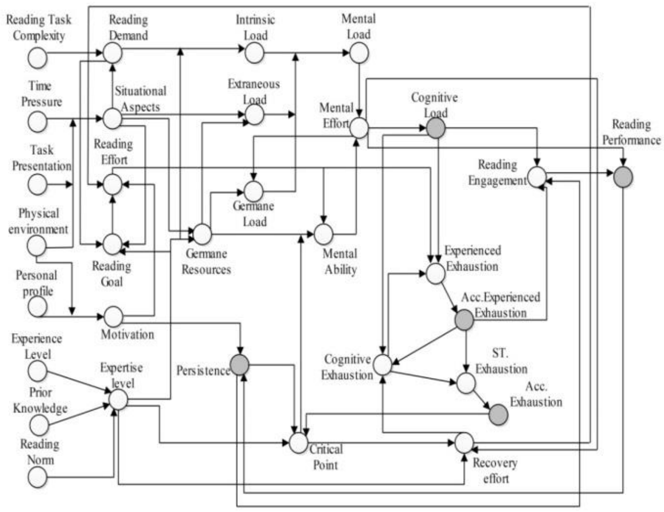

Figure 4: The Conceptual Refined Model of Cognitive Load and Reading Performance

Table 1
Nomenclatures of the Concepts Used in the Model

No.	Factors	Formal Representations
1	Reading Task Complexity	*Tc*
2	Time Pressure	*Tp*
3	Task Presentation	*Tn*
4	Physical Environment	*Pe*
5	Personal Profile	*Pp*
6	Experience Level	*El*
7	Prior Knowledge	*Pk*
8	Reading Norm	*Rn*
9	Reading Demands	*Rd*
10	Situational Aspects	*Sa*
11	Reading Goal	*Rg*
12	Reading Effort	*Rf*
13	Motivation	*Mv*
14	Expertise Level	*Ev*
15	Intrinsic Load	*Id*
16	Extraneous Load	*Ed*
17	Germane Load	*Gd*
18	Germane Resources	*Gr*
19	Mental Load	*Ml*
20	Mental Effort	*Me*
21	Mental Ability	*Ma*
22	Cognitive Exhaustion	*Ce*
23	Reading Engagement	*Rm*
24	Critical Point	*Cp*
25	Experienced Exhaustion	*Ex*
26	Recovery Effort	*Re*
27	Short Term Exhaustion	*Sh*
28	Accumulative Experienced Exhaustion	*Ax*
29	Accumulative Exhaustion	*Ae*
30	Cognitive Load	*Cl*
31	Reading Performance	*Rp*
32	Persistence	*Pr*

Next, based on the identified relationships the conceptual model was formalized with respect to time using differential equations. These equations are described as the followings:

$$\boldsymbol{Gd(t) = \gamma_{Gd}.Me(t) + (1-\gamma_{Gd}).Me(t).(1-Gr(t))} \quad (1)$$

$$Rd(t) = \eta_{rd}.Tc(t) + (1 - \eta_{rd}).Sa(t) \quad (2)$$

$$Sa(t) = \lambda_{sa}.[w_{sa1}.Tp(t) + w_{sa2}.Pe(t)] + (1 - \lambda_{sa}).[Tp(t).Pe(t).(1 - Tn(t))] \quad (3)$$

$$Ev(t) = \zeta_{ev}.(w_{ev1}.El(t) + w_{ev2}.Pk(t)) + (1 - \zeta_{ev}).Rn(t) \quad (4)$$

$$Gr(t) = \omega_{gr}.Ev(t) + (1 - \omega_{gr}).Ev(t).(1 - Sa(t))) \quad (5)$$

$$Me(t) = (1 - Ma(t)).Ml(t) \quad (6)$$

$$Ml(t) = w_{ml1}.Id(t) + w_{ml2}.Ed(t) + w_{ml3}.Gd(t) \quad (7)$$

$$Ma(t) = w_{ma1}.Rf(t) + w_{ma2}.Cp(t) + w_{ma3}.Gr(t) \quad (8)$$

$$Id(t) = Rd(t).(1 - Ev(t)) \quad (9)$$

$$Ed(t) = \beta_{ed}.Sa(t) + (1 - \beta_{ed}).Sa(t).(1 - Gr(t)) \quad (10)$$

$$Sh(t) = \mu_{st}.Ce(t) + (1 - \mu_{st}).Ax(t) \quad (11)$$

$$Ex(t) = (w_{ex1}.Cl(t) + w_{ex2}Ce(t)).(1 - Rf(t)) \quad (12)$$

$$Re(t) = \text{Pos}((w_{re1}.Cp(t) + w_{re2}.Ev(t)) - Me(t)) \quad (13)$$

$$Rm(t) = \Pr(t).[1 - (w_{rm1}.Ax(t) + w_{rm2}.Cl(t))] \quad (14)$$

$$Ce(t) = (\alpha_{ce}.Cl(t) + (1 - \alpha_{ce}).Ax(t)).(1 - Re(t)) \quad (15)$$

$$Cp(t) = \alpha_{cp}.Ev(t) + (1 - \alpha_{cp}).Pr(t).Ev(t).(1 - Ae(t)) \quad (16)$$

$$Rg(t) = \zeta_{rg}.Ev(t) + (1 - \zeta_{rg}).[w_{rg1}.Rd(t) + w_{rg2}.(1 - (Sa(t).(1 - Ev(t))))] \quad (17)$$

$$Rf(t) = \gamma_{rf}.(w_{rf}.Mv(t) + w_{rf}.Rg(t)) + (1 - \gamma_{rf}).Re(t) \quad (18)$$

$$Ae(t + \Delta t) = Ae(t) + \beta_{Ae}.(Sh(t) - Ae(t)).Ae(t).(1 - Ae(t)).\Delta t \quad (19)$$

$$Ax(t + \Delta t) = Ax(t) + \eta_{Ax}.Ex(t).(1 - Ax(t)).\Delta t \quad (20)$$

$$Cl(t + \Delta t) = Cl(t) + \beta_{Cl}.(Me(t) - Cl(t)).Cl(t).(1 - Cl(t)).\Delta t \quad (21)$$

$$Rp(t + \Delta t) = Rp(t) + \eta_{Rp}.[((1 - Me(t)).Rm(t)) - Rp(t)].(1 - Rp(t)).Rp(t).\Delta t \quad (22)$$

$$Pr(t + \Delta t) = Pr(t) + \omega_{Pr}.\left[[w_{pr1}.Mv(t) + w_{pr2}.Rp(t)] - \Pr(t) - \beta dp\right].(1 - \Pr(t)).\Pr(t).\Delta t \quad (23)$$

IV. SIMULATION RESULTS

In this section, it has shown how the dynamical model of cognitive load and reading performance was executed to simulate a number of different scenarios with various conditions of readers. Therefore, three different scenarios of three different fictional individuals (i.e., in the form of agents) are simulated. These scenarios are as the following; Agent ***A***: demanding task and the reader is expertise and less motivated, Agent ***B***: demanding task, reader is expert and highly motivated, and Agent ***C*:** demanding task, reader is not expert and less motivated. Different initial settings were used to generate the simulation traces. These initial settings are as the followings:

i. agent ***A*** {*Tc*=0.9, *Tp*=0.9, *Pe*=0.9, *Tn*=0.1, *Rn*=0.9, *Pp*=0.1, *El*=0.9, *Pk*=0.9},
ii. agent ***B*** {*Tc*=0.9, *Tp*=0.9, *Pe*=0.1, *Tn*=0.1, *Rn*=0.9, *Pp*=0.9, *El*=0.9, *Pk*=0.9},
iii. agent ***C*** {*Tc*=0.9, *Tp*=0.9, *Pe*=0.9, *Tn*=0.1, *Rn*=0.8, *Pp*=0.1, *El*=0.1, *Pk*=0.1}.

The temporal relationships in all cases are set to initial values as well. The values of accumulative exhaustion (*Ae*), reading performance (*Rp*), and persistence (*Pr*) are initialized as 0.3, where the accumulative experienced exhaustion (*Ax*) and cognitive load (*Cl*) are initialized as 0.0 and 0.1 respectively. In the same time, several parameters were used to simulate different individual characteristics and to get the most preferred conditions. The following parameters settings are used: t_{max} =500 (to represent a monitoring activity up to 4 hours), Δt=0.5, λ_{sa} = 0.9, w_{ml2}=0.4, w_{ml3}=0.1, w_{ma1}=0.3, w_{ma2}=0.3, w_{ma3}=0.3, w_{re1}=0.9, w_{re2}=0.1, $\beta_{Ae} = 0.08$, $\beta_{Cl} = 0.3$, $\omega_{Pr} = 0.9$, β_{dp}=0.01, $\eta_{Ax} = 0.03$, $\beta_{ed} = 0.9$, and $\beta_{ed} = 0.8$. Note here, the other parameter values are initialized as 0.5. These setting were obtained from previous extensive systematic experiments to determine the most suitable parameter values in the model.

A. Case# 1: Simulation Results of Cognitive Load (Cl)

In this simulation, the results of cognitive load, intrinsic, extraneous, and germane load are presented as in Figure 5. For this case, an agent A is performing a demanding reading task that requires a high mental effort to be accomplished. Nevertheless, the high expertise level has enabled a reader to cope with the demands and curbs the progression of cognitive load throughout simulation runs. However, due to the situation, i.e. a less motivated reader (as resembled among neurotic personality and at the non-ambience environment), the level of cognitive load slightly increases. This slight increase in cognitive load results from a high level of extraneous load (Figure 5(b)). Likewise, the same results also can be seen for agent B who is a person with a high expertise level, highly motivated and has a positive personality (i.e., openness) and ambience environment). Conversely, an agent C shows the opposite results due to intolerable demands (highly difficult task), no preparation, discomfort environment, and overwhelm time pressure. Moreover, agent C is not motivated to perform the task and has lack of knowledge and experiences.

B. Case #2: Simulation Results of Exhaustion (Ae)

This case simulates the formation of an accumulative exhaustion within both agents ***A*** and ***B***. Although in both scenarios, agents have some expertise and able to accommodate the task easily (low cognitive exhaustion (*Ce*)), the cognitive exhaustion is gradually triggered by the experienced of physical tiredness (*Ax*) (e.g., eyes ache and back pain). In contrast, an agent ***C*** encounters rapid increment in his /her exhaustion level. The physical and mental tiredness levels are among important factors that contribute towards the development of a high exhaustion level. In addition, low recovery from exhaustive tasks also contributes to the development of accumulative exhaustion. It means the recovery effort (*Re*) is already consumed and it is difficult for an individual to recover within a limited time. Figure 6 summarizes the simulation results of accumulative exhaustion (*Ae*) and its precursors: cognitive exhaustion (*Ce*), accumulative experienced exhaustion (*Ax*), and recovery effort (*Re*).

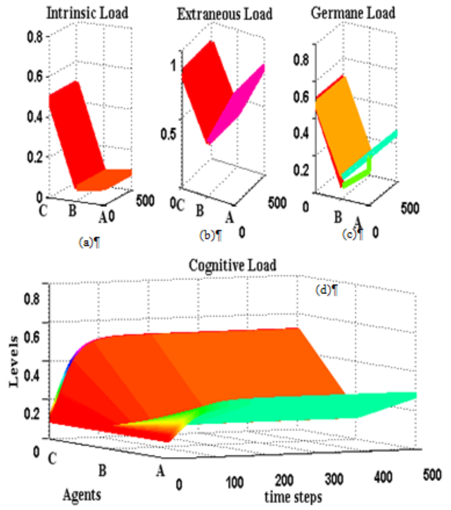

Figure 5: Simulation Results of a) Intrinsic, b) Extraneous, c) Germane and d) Cognitive Load

C. *Case #3: Simulation result of Reading Performance (Rp) and Persistence (Pr)*

In this simulation, the results of reading performance and persistence are explained as (a) and (b) respectively in Figure 7. In terms of persistence level, both agent ***A*** and ***C*** show signs that they are experiencing low level of persistence. This result is in line with [10]. However, in spite of that, agent ***B*** produces different results so that the level of persistence is drastically increases. This condition is consistent for any highly motivated individuals as they tend to develop persistence in achieving their intended goals.

Relating this result to the reading performance, it represents to which extent a reader is performing a meaningful and seamless reading process. Consequently, the level of reading performance will degrade when the cognitive load and exhaustion level gets high.. The simulation results of agent ***A***, ***B***, and ***C*** are shown in Figure 7 (b).

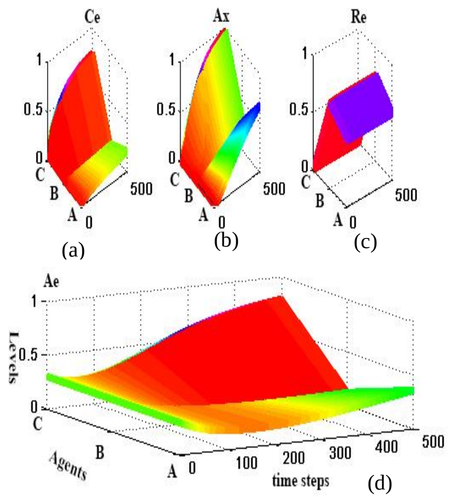

Figure 6: Simulation Results of a) Cognitive Exhaustion, b) Experienced Exhaustion, c) Recovery Efforts and d) Accumulated Exhaustion

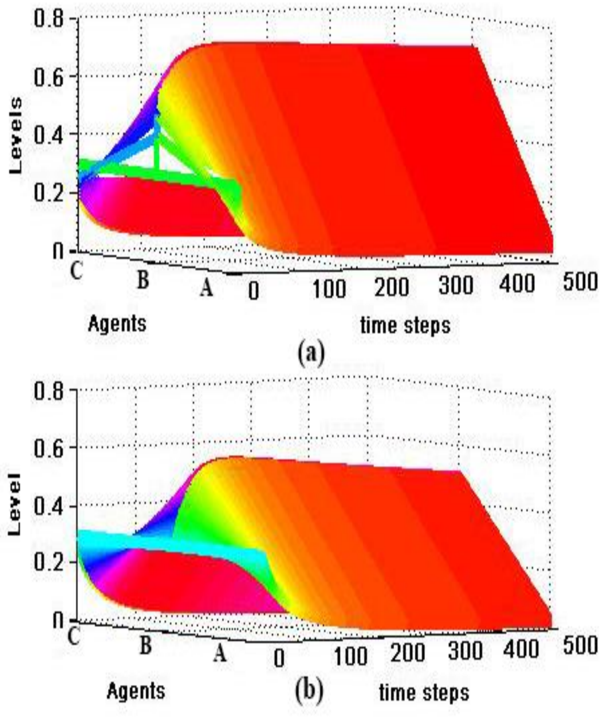

Figure 7: Simulation results of (a) Persistence and (b) Reading performance

V. AUTOMATED EVALUATION

In order to evaluation whether the model truly yields results that adherence to cognitive load literatures, a set of properties have been identified from related literatures. These properties have been specified in a language known as the Temporal Trace Language (TTL). TTL is built on atoms referring to states of the world, time points, and traces. This relationship can be presented as holds (*state*(γ, *t*), *p*) or *state(γ, t)*|= *p*, which means that state property *p* is true in the state of trace γ at time point *t* [6]. It is also comparable to the *Holds*-predicate in the Situation Calculus. Based on that concept, dynamic properties can be formulated using a hybrid sorted predicate logic approach, by using quantifiers over time and traces and first-order logical connectives such as ¬, ∧, ∨, ⇒, ∀, and ∃. TTL is used by generating a finite state space of a formal model of a system and later verifies a property written in some temporal logic specifications, through an explicit state space search. It can provide an answer in a few minute or even seconds for many models as the search always terminates (due to the finite search space). A number of simulations including the ones described in Section IV have been used as a basis for verifying and confirming identified properties.

The verification patterns obtained are:

VP1: Readers with high level of persistence tends to reduce the level of cognitive load [10].

VP1 ≡ ∀γ:TRACE, ∀t1,t2:TIME, ∀D,B1,B2, R1,R2:REAL, ∀X:AGENT
[state(γ, t1)|= persistence(X, B1) &
state(γ, t2)|= persistence(X, B2) &
state(γ, t1)|= cognitive_load(X,R1) &
state(γ, t2)|= cognitive_load(X,R2) &
t2 > t1 + D & B2 > 0.5 & B2 ≥ B1] ⇒ R2 < R1

VP2: Non-stop reading process will lead to the development of exhaustion.

$$VP2 \equiv \forall\gamma\text{:TRACE}, \forall t1, t2\text{:TIME}, \forall M1, M2, D\text{:REAL}, \forall A\text{:AGENT}$$
$$\text{state}(\gamma, t1) |= \text{accumulated\_exhaustion}(A, M1)\ \&$$
$$\text{state}(\gamma, t2) |= \text{accumulated\_exhaustion}(A, M2)\ \&$$
$$M1 \geq 0.1\ \&\ t2 = t1+D \Rightarrow M2 \geq M1$$

VP3: Reading performance is high when cognitive load is low [11].

$$VP3 \equiv \forall\gamma\text{:TRACE}, \forall t1,t2\text{:TIME}, \forall D,V1,V2,R1,R2\text{:REAL}, \forall X\text{:AGENT}$$
$$[\text{state}(\gamma, t1) |= \text{cognitive\_load}(X, B1)\ \&$$
$$\text{state}(\gamma, t2) |= \text{cognitive\_load}(X, B2)\ \&$$
$$\text{state}(\gamma, t1) |= \text{reading\_performance}(X,R1)\ \&$$
$$\text{state}(\gamma, t2) |= \text{reading\_performance}(X,R2)\ \&$$
$$t2 > t1 + D\ \&\ B1 < 0.2\ \&\ B1 \geq B2] \Rightarrow R2 < R1$$

VP4: Readers with high level of expertise possess high critical power [12] .

$$VP4 \equiv \forall\gamma\text{:TRACE}, \forall t1, t2\text{:TIME}, \forall X1, X2, C, D\text{:REAL}, \forall A\text{:AGENT}$$
$$\text{state}(\gamma, t1) |= \text{expertise\_level}(A, C)\ \&$$
$$\text{state}(\gamma, t1) |= \text{critical\_power}(A, M1)\ \&$$
$$\text{state}(\gamma, t2) |= \text{critical\_power}(A, M2)\ \&$$
$$C \geq 0.8\ \&\ t2 = t1+D \Rightarrow M2 \geq M1$$

VP5: Non-conducive learning environment increases cognitive load [13].

$$VP5 \equiv \forall\gamma\text{:TRACE}, \forall t1, t2\text{:TIME}, \forall V1, V2, Q, D\text{:REAL}, \forall A\text{:AGENT}$$
$$\text{state}(\gamma, t1) |= \text{ambience\_room}(A, Q)\ \&$$
$$\text{state}(\gamma, t1) |= \text{cognitive\_load}(A, V1)\ \&$$
$$\text{state}(\gamma, t2) |= \text{cognitive\_load}(A, V2)\ \&$$
$$Q < 0.2\ \&\ t2 = t1+D \Rightarrow V2 \geq V1$$

VI. CONCLUSION

The mission to develop intelligent systems that are capable of supporting humans proactively and in a knowledgeable manner requires special attention towards modeling the dynamic behaviour of humans' cognitive and psychological states. The integration of these dynamic models with the digital artefacts, gives them the ability to reason and perform informed actions (make connections) with humans. An attempt to develop a dynamical model of cognitive load and reading performance have been made and being refined. The refined model can be used as a building block to create a reading companion robot that assists readers when they experience the cognitive overload. In order to ensure the reliability of the model, a formal automated analysis (using Temporal Trace Language) was performed and the results showed that the model adheres to several related psychological and cognitive literature. Though the verification experiments show positive results, further tests are still needed. Thus, our next initiative would be to perform a series of human-based experiments and testing.

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