

ORIGINAL ARTICLE

ON MODELLING COGNITIVE LOAD DURING READING TASK

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ABSTRACT

One of the main challenges that hugely effect readers' performance is cognitive load. It plays a pivotal role to facilitate readers to learn, memorize, and digest a piece of novel information. However, cognitive load can also have insignificant impacts on reading task when the cognitive demands of the reading task when to solve a complex problem. This article proposed a computational model of cognitive load during reading task, based on Cognitive Load theory, to get deep understandings on the dynamics of cognitive load and how the different types of load like intrinsic, extraneous and germane load are affecting the level of cognitive load. A number of simulation experiments were conducted and the results showed that the model is able to produce realistic behaviours under different personalities and conditions. Furthermore, an automated verification was implemented to evaluate the model.

Keywords: *cognitive Load, reading and learning, simulations, formal analysis, computational modelling.*

INTRODUCTION

Reading is an important task to all individuals in order to function in today's society as it is an essential way to develop minds. Likewise, reading considers as an indispensable part to learn new concepts, knowledge, and even to build someone's character and its maturity as well. In the context of learning, reading is an integral element of learning process. In addition, it has been clearly seen that learning has been shifted from learning to read into reading to learn¹. However, despite of the remarkable advantages of reading to learn, it is always associated with a number of hurdles particularly when it caters for solving complicated tasks (e.g., solving math) and this may deter effective learning experience². For instance, the demands of reading task after a certain amount of time will yield cognitive overload that hampers reading task and therefore leaning outcomes will be degraded³.

Thus, this article majorly discusses the dynamics of cognitive load during reading task where a computational model of cognitive load is presented. To note, a model of cognitive load and reading performance has been developed earlier as seen in⁴. However, the discussion of this article mainly focuses on cognitive load during reading where detailed concepts related to cognitive load with its relationship are modelled and several relevant scenarios are simulated as well.

This article is organized as follows. Section 2 presents the important concepts of cognitive load and reading based on Cognitive Load Theory and follows by a discussion in model development in Section 3. In Section 4, several cases studies related to cognitive load during reading are presented and simulated. Later, the model was verified using Temporal Trace Language (TTL) based on several cases selected from the literatures in Section 5. Finally, Section 6 concludes the article.

COGNITIVE LOAD AND READING

The total amount of mental resources that imposed on a person while trying to solve a particular problem or to achieve a certain task is normally called cognitive load⁵. Cognitive load has attributed based on the limitation of working memory (limited capacity of a person to process novel information)². This limitation in working memory, which means the capacity and duration of processing information, is always causing load and makes an individual experiencing overloading. The effects of cognitive load are widely spread and it can be seen in many critical and demanding tasks (i.e. tasks that need fast decision to avoid the unfavourable consequences) such as driving⁶, air/train traffic control⁷. It is also quite noticeable with fighter pilots while performing military purposes where it directly affects the safety of pilot⁸.

Formalizations of Instantaneous and Temporal relations

All the identified relations were formalized using differential equations. Instantaneous relations

refer to the direct contribution of related factors, which means no change will happen with respect to time. Equations 1 to 16 represent the formalization of the instantaneous relation.

Table -1 Nomenclatures of Factors in Cognitive Load

No	Factors	Descriptions	Formal Representation
1	<i>reading task complexity</i>	difficult reading task that someone must read ¹²	T_c
2	<i>personal profile</i>	personality types such as openness or neuroticism ¹³	P_p
3	<i>time pressure</i>	the required time to get a reading task fully done ¹⁵	T_p
4	<i>physical environment</i>	the effects of the environment to readers (e.g. noise, brightness, and temperature) ³	P_e
5	<i>task presentation</i>	the way the task is presented to the reader in form of a text or a graph ¹¹	T_n
6	<i>experience level</i>	someone's experience towards a particular reading task ³	E_l
7	<i>prior knowledge</i>	the related knowledge that someone own ¹⁴	P_k
8	<i>reading norm</i>	the ability of someone to read fluently	R_n
9	<i>reading demand</i>	the amount of demands or needs that reading task imposes on readers ³	R_d
10	<i>reading effort</i>	the amount of effort someone wants to contribute to achieve reading task ¹⁵	R_f
11	<i>reading goal</i>	the willingness of someone to stay focus while performing a reading task ¹⁵	R_g
12	<i>situational aspects</i>	the combination of the external variables like time pressure, task presentation, and physical environment	S_a
13	<i>motivation</i>	refers to someone's desire to be continually interested in doing a task ¹⁶	M_v
14	<i>expertise level</i>	refer to someone expert in terms of knowledge and experience	E_v
15	<i>cognitive ability</i>	the ability of someone to perform a task easily	C_a
16	<i>intrinsic load</i>	the load that is imposed by the task itself ^{3,10,17}	I_d
17	<i>extraneous load</i>	the load that is imposed by the external variables ^{3,10,17}	E_d
18	<i>germane load</i>	the load that achieves learning outcomes ^{3,10,17}	G_d
19	<i>mental load</i>	the total amount of load imposed on a reader by task and environment characteristics ^{3,10,17}	M_l
20	<i>mental effort</i>	the amount of capacity or resources that is allocated by the reader to accommodate the task demands ^{3,10,17}	M_e
21	<i>cognitive load</i>	the amount of mental resources being used by a reader to accomplish a reading task ^{3,10,17}	C_l
22	<i>critical point</i>	the amount of effort someone can generate without becoming exhausted ¹⁵	C_p
23	<i>persistence</i>	someone's state to continue performing a reading task ¹⁶	P_r
24	<i>germane resources</i>	reader's resources to handle intrinsic cognitive load ^{3,10,17}	G_r

$$El(t) = a_{el} \cdot Be(t) + (1 - a_{el}) \cdot Ep(t) \quad (1)$$

$$Pk(t) = \sigma_{pk} \cdot Bk(t) + (1 - \sigma_{pk}) \cdot Lc(t) \quad (2)$$

$$Rd(t) = [\eta_{rd} \cdot Tc(t) + (1 - \eta_{rd}) \cdot Sa(t)] \cdot (1 - Ca(t)) \quad (3)$$

$$Rf(t) = \gamma_{rf} \cdot [w_{rf1} \cdot Mv(t) + w_{rf2} \cdot Pp(t)] + (1 - \gamma_{rf}) \cdot [w_{rf3} \cdot Rg(t) + w_{rf4} \cdot Re(t)] \quad (4)$$

$$Mv(t) = \lambda_{mv} \cdot El(t) + (1 - \lambda_{mv}) \cdot Pp(t) \quad (5)$$

$$Rg(t) = \zeta_{rg} \cdot Ca(t) + (1 - \zeta_{rg}) \cdot [w_{rg1} \cdot Rd(t) + w_{rg2} \cdot (1 - Sa(t)) \cdot (1 - Ca(t))] \quad (6)$$

$$Ev(t) = \zeta_{ev} \cdot El(t) + (1 - \zeta_{ev}) \cdot Pk(t) \quad (7)$$

$$Id(t) = Rd(t) \cdot (1 - Ev(t)) \quad (8)$$

$$Sa(t) = \lambda_{sa} \cdot [w_{sa1} \cdot Tp(t) + w_{sa2} \cdot Pe(t)] + (1 - \lambda_{sa}) \cdot [Tp(t) \cdot Pe(t) \cdot (1 - Tn(t))] \quad (9)$$

$$Ca(t) = w_{ca1} \cdot El(t) + w_{ca2} \cdot Pk(t) + w_{ca3} \cdot Rn(t) \quad (10)$$

$$Ed(t) = Sa(t) \cdot (1 - Ev(t)) \quad (11)$$

$$Gd(t) = \mu_{gd} \cdot Gr(t) + (1 - \mu_{gd}) \cdot (1 - Rd(t)) \cdot (1 - Gr(t)) \quad (12)$$

$$Gr(t) = \omega_{gr} \cdot Ev(t) + (1 - \omega_{gr}) \cdot (1 - Sa(t)) \cdot (1 - Ev(t)) \quad (13)$$

$$Ml(t) = (1 - Me(t)) \cdot [\mu_{ml} \cdot [B_{ml} \cdot Id(t) + (1 - B_{ml}) \cdot Ed(t)] + (1 - \mu_{ml}) \cdot [Id(t) \cdot Ed(t) \cdot (1 - Gd(t))]] \quad (14)$$

$$Me(t) = B_{me} \cdot Rf(t) + (1 - B_{me}) \cdot Cp(t) \quad (15)$$

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

On the other hand, temporal relations refer to factors that changeable over time due to the interaction between two or more instantaneous factors. Equations 17 to 18 represent the formalization of the temporal relations.

$$Pr(t+\Delta t) = Pr(t) + \omega_{pr} \cdot [w_{pr1} \cdot Mv(t) + w_{pr2} \cdot Rp(t)] - Pr(t) \cdot Bdp \cdot \Delta t \quad (17)$$

$$Cl(t+\Delta t) = Cl(t) + w_{cl} \cdot [Pos(Ml(t) - Me(t)) \cdot (1 - Cl(t)) - Pos(-(Ml(t) - Me(t)) \cdot Cl(t))] \cdot \Delta t \quad (18)$$

In both of instantaneous and temporal equations, several parameters are used. For example, from equations (1) and (10), the parameters a_{el} and w_{ca1} represent the regulation factors while ω_{pr} (from equation 17) represents the rate change of the temporal relationship. Furthermore, the positive operator Pos is introduced as well and defined by $Pos(x) = (x + |x|) / 2$, or alternatively; $Pos(x) = x$ if $x \geq 0$ and 0 else. Detailed discussions on relevances to formalize conceptual dynamic models with the respect to instantaneous and temporal relations can be found in ^{4,18}

SIMULATION RESULTS

In this section, the computational model of cognitive load was programmed and executed using numerical programming language (i.e., Matlab) to generate several traces that mimic the dynamics behaviour of cognitive load related to readers when they perform a demanding reading task. To show the results of this simulation, three different cases were simulated that demonstrate different level of readers' competence skills. These cases are 1) high competence skills, 2) moderate competence skills, and 3) low competence skills. The duration of the simulation is up to 500 time steps divided equally into three time frames (to simulate four hours of reading), with these simulation parameters settings; $\Delta t = 0.2$, $a_{el} = \sigma_{pk} = 0.8$, $w_{ca1} =$

$w_{ca2} = w_{ca3} = 0.33$, $\zeta_{rm} = 0.9$, $\mu_{lc} = 0.1$, $\alpha_{ex} = 1$, $w_{re1} = 0.9$, $w_{re1} = 0.1$, $B_{dp} = 0.0001$, $B_{ae} = 0.9$. All other parameters were initialized using value = 0.5.

Case 1#: High Competence Skills

In this case, readers are skilled enough (having good knowledge and experience to accomplish the task) with positive personalities to perform a demanding reading task. Besides, reading task is gradually getting complex. Moreover, three time frames are simulated to represent the demands that the task and the environment imposed on the readers. For example, at time frame one reading task is not difficult, time pressure is low and the environment is suitable to perform the task. These conditions are getting moderately and highly demands in time frame two and three respectively as the level of task difficulty and environment conditions are becoming not preferred. Table 2 presents the initial values of case 1 with respect to time frames. The result of these conditions shows that the level of mental load and cognitive load are getting low in spite of the demand levels. This is because of the ability of readers to exert more mental effort. Figure 2 shows the simulation result of case 1.

Table -2 Reader with high competence skills

Inputs Factors	Initial Values		
	F1	F2	F3
Tc	0.1	0.25	0.9
Tp	0.1	0.25	0.9
Pe	0.1	0.25	0.9
Tn	0.9	0.25	0.1
Rn	0.9	0.9	0.9
Be	0.9	0.9	0.9
Bk	0.9	0.9	0.9
Pp	0.9	0.9	0.9

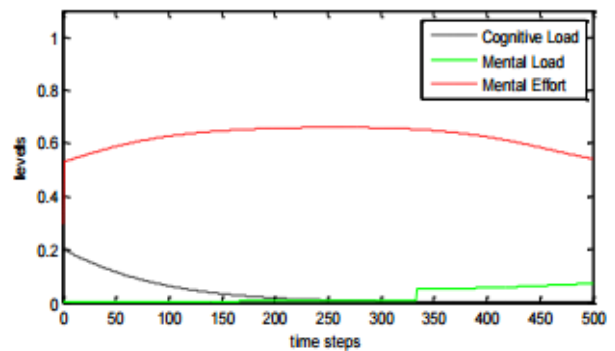


Figure -2 Simulation Result of Case 1.

Case 2#: Moderate Competence

Skills In this case, readers are moderately skilled to perform difficult reading task and their personality is somehow positive (e.g., openness personality towards reading task). Readers' skills are measured in terms of their ability to read

and their prior knowledge and experiences toward the subject matter. To simulate readers' conditions, three different time frames are designed, similarly in case 1. Table 3 presents the initial values of case 2 with respect to time frames. The simulation results from this case indicates that cognitive load level is increasing at time frame three due to the high demands of the reading task and also the demands of the environment. It means readers are no longer capable to cope with demands as their mental load is higher than their mental effort. Figure 3 shows the simulation result of case 2.

Table -3 Readers with Moderate Competence Skills

Inputs Factors	Initial Values		
	F1	F2	F3
T_c	0.1	0.25	0.9
T_p	0.1	0.25	0.9
P_e	0.1	0.25	0.9
T_n	0.9	0.25	0.1
R_n	0.25	0.25	0.25
B_e	0.25	0.25	0.25
B_k	0.25	0.25	0.25
P_p	0.25	0.25	0.25

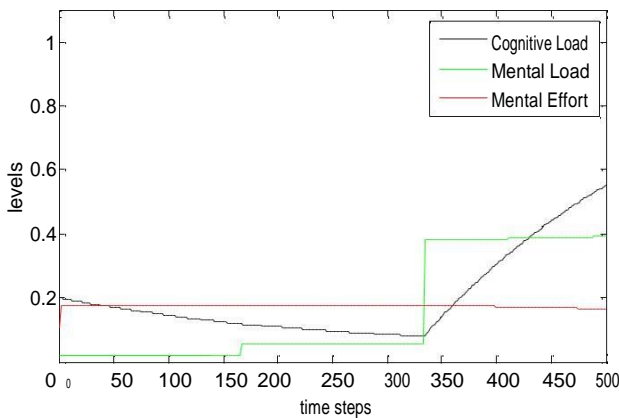


Figure -3 Simulation Results of Case 2.

Case 3#: Low Competence Skills

In this case, readers are not skilled and their personalities is negative (e.g., neurotic personality toward reading task) to perform a demanding reading task that requires high mental efforts. Reading task is gradually getting complex and readers are having no enough knowledge and experience to accomplish the task. Likewise, in case 1 and case 2, three time frames are made to represent the gradual increase in task and environment demands. Table 4 presents the initial values of case 3 with respect to time frames. The simulation result of this case indicates that cognitive load level is increasing dramatically at time frame three. The increment of cognitive load level is due to

the mental load level that is imposed on readers is higher than their mental effort. Figure 4 shows the simulation result of case 3.

Table -4 Reader with Low Competence Skills

Inputs Factors	Initial Values		
	F1	F2	F3
T_c	0.1	0.25	0.9
T_p	0.1	0.25	0.9
P_e	0.1	0.25	0.9
T_n	0.9	0.25	0.1
R_n	0.1	0.25	0.25
B_e	0.1	0.1	0.1
B_k	0.1	0.1	0.1
P_p	0.1	0.1	0.1

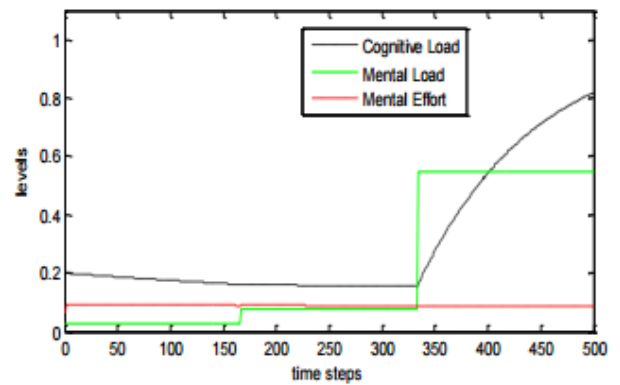


Figure -4 Simulation result of Case 3.

EVALUATION: AUTOMATED VERIFICATION

In order to verify whether the model indeed generates results that adherence to related cognitive load literatures, a set of properties have been identified from related literatures. Therefore, these properties will answer whether the model produces results that are coherent with the literature. A typical example of a property that can be explored and checked is whether no unexpected conditions occur (e.g. boundary testing; cognitive load < 0 mental effort > 1) In addition, by executing a large number of simulations and verifying these properties against the resulting traces, we can easily identify potential logical errors. To allow the verification process to take place, these properties have been specified in a language called Temporal Trace Language (TTL). TTL is built on atoms referring to states of the world, time points, and traces¹⁹. This relationship can be presented as a state $(\gamma, t, \text{output}(R)) \models p$, means that state property p is true at the output of role R in the state of trace γ at time point t. For this purpose, special software has been developed for TTL, featuring both a property editor and a checking tool that enables formal verification of such properties against a set of simulated traces.

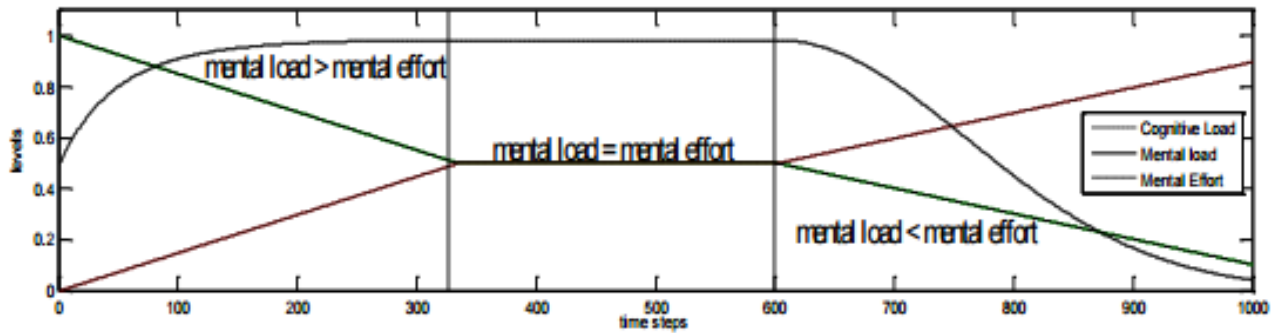


Figure -5

A number of simulations including the ones described in previous subsection have been used as basis for the verification and were confirmed.

VP1: Higher Mental Load Will Increase Cognitive Load

If the mental load level is increasing throughout time and it is higher than the current mental effort, later it will increase the cognitive level (as in Figure 5).

```
VP1 =  $\forall \gamma$ : TRACE,  $\forall t_1, t_2$ :TIME,  $\forall R_1, R_2, V_1, V_2, D_1, D_2$ :REAL
[ state( $\gamma, t_1$ )= mental_load( R1 ) &
state( $\gamma, t_2$ )= mental_load( R2 ) &
state( $\gamma, t_1$ )= mental_effort(V1) &
state( $\gamma, t_2$ )= mental_effort(V2) &
state( $\gamma, t_1$ )= cognitive_load(D1) &
state( $\gamma, t_2$ )= cognitive_load(D2) &
 $t_1 < t_2 \ \& \ R_1 > V_1 \ \& \ R_2 > V_2 ] \Rightarrow D_2 \geq D_1$ 
```

VP2: Variable v Between Boundaries

For all time points t between t_b and t_e in trace γ if at t the value of v is x , then minimum value $< x <$ maximum value.

```
VP2 =  $\forall \gamma$ : TRACE,  $\forall t, t_b, t_e$ :TIME,  $v$ :VAR, max, min:REAL
[ state( $\gamma, t$ )= has_value(v,x) &
 $t_b \leq t \leq t_e \Rightarrow \min < x < \max$ 
```

This formal specification can be used to check whether a variable stays between certain observed boundaries. For example, the germane and mental load levels should never become lower than 0 or higher than 1.

VP3: Non-conductive Learning Environment Increases Cognitive Load

If the non-conductive environment has been observed, it will contribute towards the development of cognitive load.

```
VP3 =  $\forall \gamma$ : TRACE,  $\forall t_1, t_2$ :TIME,  $\forall V_1, V_2, H_1, H_2, D$ :REAL
[ state( $\gamma, t_1$ )= physical_environment( V1 ) &
state( $\gamma, t_2$ )= physical_environment( V2 ) &
state( $\gamma, t_1$ )= cognitive_load(H1) &
state( $\gamma, t_2$ )= cognitive_load(H2) &
 $V_1 > 0.8 \ \& \ t_1 < t_2 + D \ \& \ V_1 \leq V_2 ] \Rightarrow H_2 \geq H_1$ 
```

VP4: Higher Mental Effort Decreases Cognitive Load

If the mental effort level higher than mental load, cognitive load will decrease (in Figure 2).

```
VP4 =  $\forall \gamma$ : TRACE,  $\forall t_1, t_2$ :TIME,  $\forall R_1, R_2, V_1, V_2, H_1, H_2, D$ :REAL
[ state( $\gamma, t_1$ )= mental_effort( R1 ) &
state( $\gamma, t_2$ )= mental_effort( R2 ) &
state( $\gamma, t_1$ )= mental_load(V1) &
state( $\gamma, t_2$ )= mental_load(V2) &
state( $\gamma, t_1$ )= cognitive_load(H1) &
state( $\gamma, t_2$ )= cognitive_load(H2) &
 $t_1 < t_2 + D \ \& \ R_1 > V_1 \ \& \ R_2 > V_2 ] \Rightarrow H_1 \geq H_2$ 
```

VP5: Variable v1 Above v2

For all time points t between t_b and t_e in trace γ if at t the value of v_1 is x_1 , and the value of v_2 is x_2 then minimum $x_1 \geq x_2$.

```
VP5 =  $\forall \gamma$ : TRACE,  $\forall t, t_b, t_e$ :TIME,  $v_1, v_2$ :VAR,  $x_1, x_2$ :REAL
[ state( $\gamma, t$ )= has_value(v1,x1) &
state( $\gamma, t$ )= has_value(v2,x2) &
 $t_b \leq t \leq t_e \Rightarrow x_1 \geq x_2$ 
```

Property P5 is used to verify whether a variable value stay above another variable value during a specified interval. For example, during the formation of cognitive load, the mental effort should never exceed the mental load (as in Figure 5).

CONCLUSION

In this article, a formal model of cognitive load during reading is introduced. The model was developed based on important concepts in Cognitive Load Theory. This theory explains cognitive load during reading tasks based on three main types of load related to task characteristics, which are intrinsic, extraneous, and germane load. Furthermore, it shows how readers' characteristics such as motivation and expertise level play important role to determine the level of cognitive load. Together, reading task characteristics and reader characteristics are used to develop the computational model of cognitive load. This model was simulated to represent readers' cognitive load under different conditions. The results showed that the model exhibits realistic patterns of cognitive load during reading. An automated verification has been implemented to prove the correctness of the model based on selected cases. The proposed model provides deep understandings on

the occurrence of cognitive load while reading and these understandings help in designing a software agent to support readers. In the next step, the proposed model can be used to develop an assistive robot that supports readers during reading task.

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