Measuring Cognitive Loads Based on the Mental Chronometry Paradigm

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***Abstract*—The cognitive load theory distinguishes three types of cognitive loads: intrinsic, extraneous, and germane. Measuring each cognitive load individually is challenging. In this study, we developed a measurement method based on the mental chronometry paradigm. Participants played 8 by 8 Reversi games with a computerized experimental environment. A 2 x 2 x 2 mixed design experiment was performed wherein the three types of cognitive loads were manipulated. The experimental results supported almost all our predictions drawn from assumed cognitive processes, implying a possibility that our methodology can be used for measuring cognitive loads.**

Keywords - cognitive load theory; intrinsic; extraneous; germane

I. INTRODUCTION

The cognitive load theory (CLT) has played a central role in designing learning environments [1][2]. The theory distinguishes three types of cognitive loads: intrinsic, extraneous, and germane. Intrinsic load is defined as the basic cognitive load required to perform a task. As the difficulty of the task increases and the degree of expertise of the performer decreases, there is an increase in the intrinsic load. Extraneous load is defined as the wasted cognitive load that does not relate to the primary cognitive activities, but emerges reluctantly. One reason that the extraneous load occurs is due to the inappropriate design of the learning material. For example, when the related information is not properly arranged, the extraneous load increases by the efforts of performing irrelevant searches to gather the related information. Germane load is defined as the load used for learning, such as for constructing schemata activities.

Figure 1 illustrates the relationship among the three cognitive loads [3]. Figure 1 (a) illustrates the state in which the cognitive load exceeds the limits of the performer's working memory capacity due to the increase in the extraneous load. In this situation of overload, learners make enormous errors, spend too much time performing the task, and occasionally, may be unable to perform the task. Figure 1 (b) shows cognitive loads that fall within a range where learners perform a task easily and show good results. CLT proposes that in such a situation where there is memory capacity to spare, it is important to increase the germane load to activate learning activities, as illustrated in Figure 1 (c).

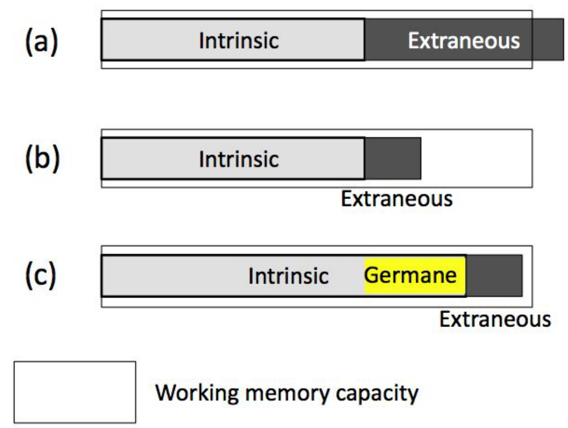

Figure 1. The three types of cognitive loads.

For measuring such cognitive loads, multiple measurement approaches have been developed. The first methodology is based on participants' subjective ratings. Two primary indexes are well known: NASA-Task Load Index (NASA-TLX) [4] and SWAT, which includes three measures: time load, mental effort load, and psychological stress load [5]. These indexes measure one-dimensional cognitive loads. Recently, some trials wherein each of the three types of cognitive loads is separately measured have been developed [6][7][8][9].

Another approach attempts to measure the cognitive loads objectively based on task performances. A representative method is to estimate cognitive loads by secondary task performance [8][10]. Participants are required to respond to a stimulus as a secondary task while engaging in a primary task wherein high cognitive loads are assumed when the response time of the secondary task is longer. In addition, psychophysiological measures, such as cardiac activity, electro-oculogram, respiration, and event-related potentials, have also been used recently [10].

Measuring cognitive loads is a big challenge in CLT. In this study, we try to measure cognitive loads based on the mental chronometry paradigm [11]. Mental chronometry assumes that reaction time (RT) is reflected by the amount or the number of stages of cognitive processing. Each type of cognitive load arises from related cognitive processing. In this paper, we examine the RT of participants when engaging in a task is predictable based on assumed cognitive loads that arise from the participants' cognitive processing.

In the following, first, we will present our cognitive model, and how each of the three cognitive loads appears based on the model in Section 2. In Section 3, we will present experimental settings. Then, in Section 4, we will present our predictions

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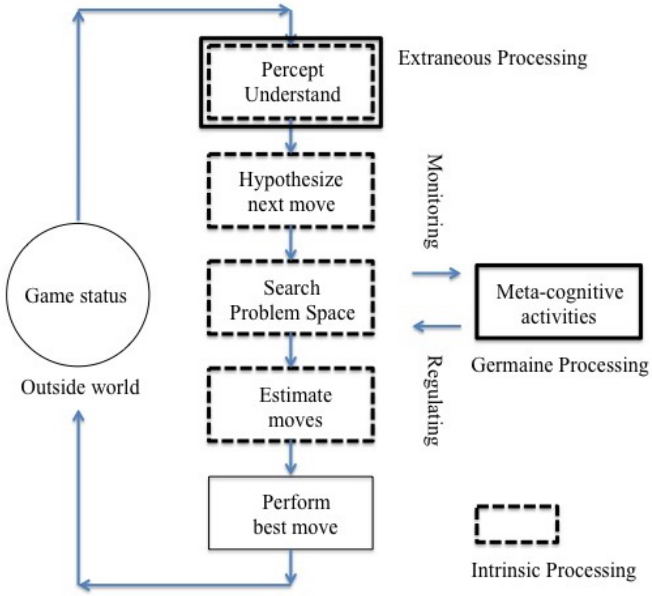


Figure 2. Assumed cognitive processing and intrinsic, extraneous, and germane cognitive loads.

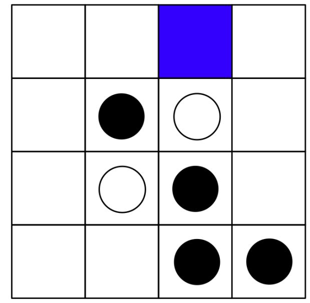
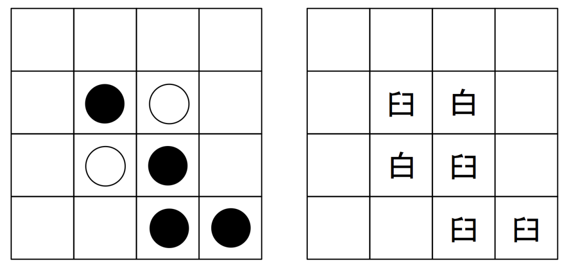


Figure 3. An example screen shot in the low intrinsic load condition wherein the participant's best move (shaded square) is presented.



(a) Low extraneous load (b) High extraneous load

Figure 4. Example screen shots in low and high extraneous load conditions.

that are expected to be observed if our assumptions in our model are valid, and all of those are supported in Section 5. The discussion and conclusions are drawn in Section 6.

II. Manipulation of Cognitive Loads

In this study, the three types of cognitive loads are more directly and individually manipulated. The task used in our experiment is the 8 by 8 Reversi game. Figure 2 shows the assumed cognitive processing of participants who engage in the task. First, they perceive the pattern of discs arrangement, and understand the game status. Then they hypothesize a next move in which their own disc is placed on one of the possible locations on the board and predict changes in the disc arrangement. The arrangement changes each time the participant and their opponent takes a turn. Participants search the problem space of the disc arrangements and determine the best move based on the estimation of each possible move, and actually perform the next move.

A. Intrinsic load

To determine the next move, the intrinsic cognitive load arises in every stage of cognitive processing, as depicted in Figure 2. In the low intrinsic load condition of our experiment, an advisor computer agent hints at the participants' possible next move; therefore, the intrinsic cognitive processing of the participants is minimized (see Figure 3). In the high intrinsic load condition, there are no hints presented.

B. Extraneous load

Figure 4 shows an example disc arrangement of low and high extraneous load conditions. When the low extraneous load condition is considered as the control condition, normal black and white discs are presented, whereas when the high extraneous load condition is considered, two kinds of Japanese letters (whose meanings are white and mortar, respectively) are presented. In the latter condition, there is high cognitive load functioning from the extraneous load in the perception and understanding stage because the two letters are perceptually similar.

C. Germane load

The germane cognitive processing was manipulated based on the experimenter's instruction. The intrinsic and extraneous cognitive loads were caused by performance-based processing whereas the germane load was due to learning-based processing. In this study, learning means to find effective heuristics and strategies of disc moves in order to win. To perform these kinds of activities, participants need to monitor and regulate their cognitive processing reflectively from the meta-cognitive perspective. In the high germane load condition, in order to let the participants perform the germane cognitive processing more actively, they were told to report the effective heuristics that were learned after games, whereas in the low germane load condition, there were no such instructions.

III. Experiment

A. Apparatus

Figure 5 shows the overall configuration of our experimental system [12]. In our experimental environment, a participant plays the 8 by 8 Reversi games against a virtual opponent (i.e., opponent agent) on a computer. In the low intrinsic load condition, the virtual partner (i.e., partner agent) assists the participant in selecting winning moves. Both agents, opponent and partner, are controlled by a Reversi engine, Edax, which suggests the best move by assessing future states in the game. The opponent's competence can be controlled by setting the

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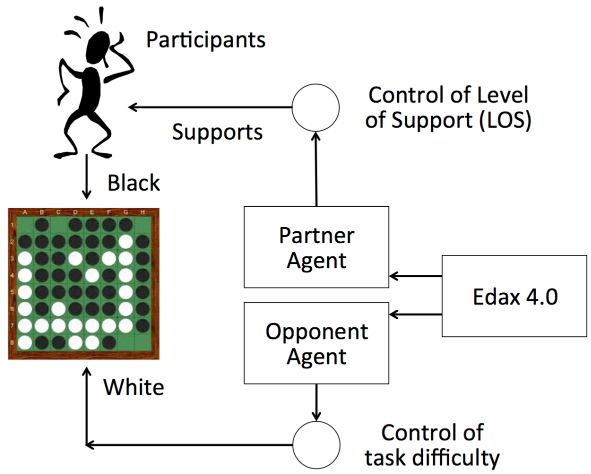

Figure 5. Overall configuration of the Reversi-based learning environment.

maximum depth to which Edax searches for future game states. The partner agent recommends the candidate's best move among valid squares before the participant makes a move.

B. Experimental design and procedure

A 2 x 2 x 2 mixed design experiment was performed: the three factors comprised (1) the intrinsic load factor (between: low and high), (2) the extraneous load factor (within : low and high), and (3) the germane load factor (between: low and high).

C. Participants and Procedure

A total of 40 undergraduates in Nagoya University participated in our experiment. All participants were not expert in playing Reversi even though they had experiences to play the game. Ten, ten, eleven, and nine participants were assigned to each of the intrinsic and germane conditions: low and low, low and high, high and low, and high and high, respectively.

Participants played a total of ten games, half of which (1st, 3rd, 5th, 7th, and 9th) were performed in the low extraneous condition and the other half (2nd, 4th, 6th, 8th, and 10th) were performed in the high extraneous condition. Participants started each game at the initial stage where 32 discs had already been placed on the board. Before the primary games, participants performed one training game for understanding the manipulation of the experimental system.

IV. Predictions

If we successfully manipulate the three factors relating to intrinsic, extraneous, and germane loads, and RT is determined based on the amount of cognitive processing that causes each of the cognitive loads assumed in Figure 2, the following predictions are expected to be verified.

A. Germane processing manipulation

A significant main effect of the germane load factor is confirmed. This indicates that RT in the high germane load condition is longer than RT in the low germane load condition.

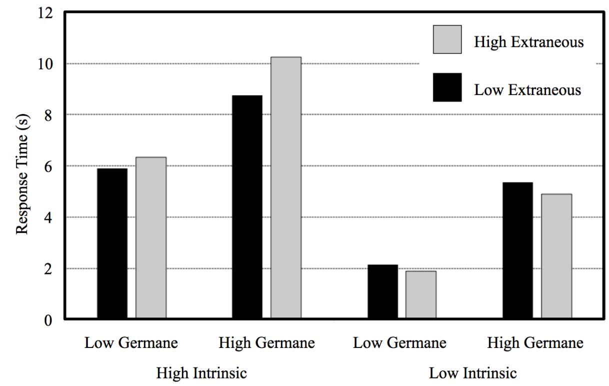

Figure 6. Result of Experiment

B. Intrinsic processing manipulation

A significant main effect of the intrinsic load factor is confirmed. This indicates that RT in the high intrinsic load condition is longer than RT in the low intrinsic load condition.

C. Extraneous processing manipulation

Significant interaction was found between the intrinsic and extraneous load factors. There is a simple main effect of the extraneous factor at the high intrinsic load condition, but no effect at the low intrinsic load condition. In the low intrinsic load condition, the perception and understanding stages are not crucial because it is possible to determine the next move without cognitive processing at these stages.

V. Result

Figure 6 presents the result of the experiment. The vertical axis shows average RT for each of the conditions. The horizontal axis shows the four experimental conditions of the intrinsic and germane load factors. The legend shows two experimental conditions of the extraneous load factor.

The statistical analysis shows the following: (1) the main effect of the germane load factor reached significance ($F(1, 36) = 27.23$, $p < 0.01$). There was no interaction observed between the germane load factor and the other two factors ($F(1, 36) < 1$, n.s. with intrinsic; $F(1, 36) < 1$, n.s. with extraneous); (2) the main effect of the intrinsic load factor reached significance ($F(1, 36) = 46.77$, $p < 0.01$). There was an interaction with the extraneous load factor ($F(1, 36) = 4.55$, $p < 0.05$), but no interaction with the germane load factor ($F(1, 36) < 1$, n.s.); (3) the main effect of the extraneous load factor did not reach significance ($F(1, 36) < 1$, n.s.). But, as mentioned above, an interaction between the extraneous and intrinsic load factors was detected. However, the simple main effect of the extraneous load factor at the high intrinsic load condition did not reveal significant differences. These results supported the first two predictions and partially supported the last prediction.

VI. Discussion and Conclusions

In this study, we presented a cognitive model on which we hypothesized three types of cognitive loads. Based on the assumptions, we manipulated the intrinsic load by help information, the extraneous load by task representation, and the germane load by an experimenter's instruction. We predicted experimental results that should be observed if the assumption and manipulation are valid.

The experimental results confirmed almost all predictions, thus supporting our methodological hypothesis: we can measure the three types of cognitive loads based on RT with the manipulation of the three types of cognitive processing relating to intrinsic, extraneous, and germane cognitive loads.

One limitation is that the simple main effect of the extraneous factor at the high intrinsic load condition was not detected, even though the interaction between extraneous and intrinsic factors was found. This implies that our manipulation for controlling the extraneous load by replacing black and white discs with perceptually similar Japanese characters did not function well. Another manipulation of the extraneous load should be tested in further research.

More importantly, in the current experiment, we only discussed RT while engaged in the task. Additionally, task performances and learning effects should be analyzed. Especially the amount of germane load, as learning-based activities, may affect learning effects while the intrinsic and extraneous loads, as performance-based activities, may influence task performances.

Another crucial step is to investigate this methodology based on the mental chronometry paradigm combined with the methodology based on participants' subjective ratings. The combination of such subjective and objective measurements may lead to more stable foundations for CLT.

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