Estimation of Trade-off between Costs of Preprocessing and Primary Processing

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Abstract

People often conduct preprocessing to simplify primary processing. Usually, there is a trade-off between the costs of performing preprocessing and primary processing. Therefore, the utility of preprocessing differs depending on the task complexity. We conducted three experiments to find out whether people could adaptively estimate the utility of preprocessing and then take rational action. The overall result was that in performing a high complexity task, almost all the participants made a rational choice. However, for a low complexity task, the participants gradually learned to conduct preprocessing despite it not being effective. These results were explained based on theoretical perspectives proposed in previous studies.

Keywords: Strategy selection; Task environment; Cost; Time; Preprocessing

Introduction

When people engage in a task, they often create and conduct an additional preliminary task in order to conduct the main task more easily by using the result of the additional task. For example, people create preliminarily index cards for documents so that needed documents can be easily found. Moreover, people program preliminarily macros on a computer so that data can be easily processed later. In this study, we call such preliminary processing “preprocessing”. People conduct preliminarily preprocessing so that primary processing in the task can be easily carried out. Preprocessing is often performed in our daily lives.

Kirsh (1996) referred to a “complementary action” which redesigns a task environment before engaging in the task in order to complete the task easily. He explained: “Complementary actions are a part of a strategy for restructuring the environment to improve the speed, accuracy, and robustness of cognitive processes” (p. 442). Such complementary actions taken before engaging in a task are also considered to be preprocessing. Moreover, Martin and Schwartz (2009) described preprocessing as an expertised action and call it an “adaptive pattern” in their manuscript. They stated that “in the adaptive pattern, people take an initial period to explore or adapt their ideas, practices, and/or environment. They are slower to start, but they can make up the lost time if they make an appropriate adaptation” (p. 372).

When preprocessing is conducted, the cost in primary processing is reduced. However, since conducting the preprocessing itself incurs a cost, there is a trade-off between the costs of preprocessing and primary processing. In such a situation, the utility of preprocessing seems to differ depending on the task complexity. When primary processing is conducted in a task without preprocessing, the task completion time increases with the task complexity. In contrast, when preprocessing is conducted for a certain period of time, it is considered that the increase in total task completion time for preprocessing and primary processing will be reduced, compared to the increase in the task completion time without preprocessing. Figure 1 illustrates our basic concept, showing the utility of preprocessing in relation to the task complexity. As shown in Figure 1, from the point where the task complexity (the amount of processing) exceeds a threshold level, the effectiveness of the preprocessing becomes significant. The utility of preprocessing differs depending on the task complexity; therefore, people should decide whether or not preprocessing is worthwhile depending on the situation.

Many researchers have studied cost estimation in situations where there is a trade-off between the costs of two different types of processing, e.g., a trade-off between processing using external resources (called external processing) and internal processing (Gray & Fu, 2004; O’Hara & Payne, 1998). In these studies, it was revealed that people adaptively estimate the costs of external processing and internal processing, and effectively adjust the usage of external resources depending on the cost of their use. Moreover, Matthew and Anderson (2009) found that people could adaptively determine whether or not external resources should be used depending on the task complexity. These studies show that people can adaptively estimate and allocate the costs of external processing and internal processing. On the other hand, in the current study, we investigate cost estimation in a situation where a different task needs to be conducted as preprocessing in order to reduce the cost of primary processing. The purpose of this study is to investigate whether people can adaptively estimate the utility of preprocessing and take rational action when there is a trade-off between the costs of preprocessing and primary processing as described above.

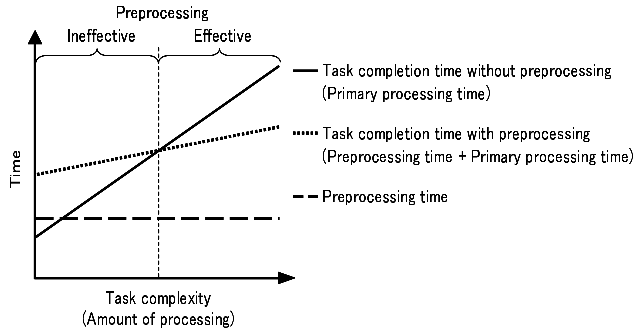

Figure 1: Concept diagram of trade-off between costs of preprocessing and primary processing

Experimental task

In the following experiments, we used a routine task of transcribing scores from test sheets to a tally sheet. In this task, fifty test sheets were prepared. On each test sheet, a student ID number was printed in the upper left and a test score in the center. In the experiments, three trials were conducted. In each trial, all the scores on the fifty individual test sheets had to be transcribed to a tally sheet to correspond to each student ID number.

Task complexity Each student ID number consisted of an eleven-digit number that encoded four categories, Grade, Major, Course, and Individual number. We set up a situation in which there were two grades, two majors, and five courses, and also there were twenty students in each course. Each student ID number on the test sheet was represented differently from that of the tally sheet, but could be collated by a certain transformation rule. In order to find the right place to fill out in the tally sheet, the student ID number on the test sheet needed to be transformed by the rule so that the transformed number could be found in the tally sheet (Figure 2). In the high task complexity condition, the participants had to calculate the student ID numbers on the test sheets for the transformation using a certain formula. On the other hand, in the low complexity condition, a student ID number correspondence table was given to the participants for the transformation so that they could find the referred numbers in the tally sheet without performing a calculation.

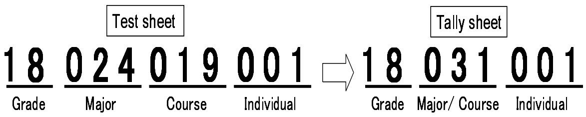

Figure 2: Transformation of student ID number; In the high task complexity condition, a transforming formula was used as follows: (1) add Major number to Course number ($24+19=43$). (2) multiply the first digit by the second digit of the result of (1) ($4\times 3=12$). (3) subtract the result of (2) from the result of (1) ($43-12=31$). In the low task complexity condition, a correspondence table was used to transform the student ID numbers.

Preprocessing To carry out the preprocessing, a desk space was available for participants. Initially, the test sheets were arranged in random order and handed to the participants. They could rearrange the test sheets on the desk space so that they could group the test sheets according to the categories of Major and Course numbers. By preliminarily grouping the test sheets, the participants could transform the student ID numbers of a bundle of multiple test sheets in the same Major and Course number at one time. There was no need to transform each student ID number on each test sheet one by one. Therefore, the participants could reduce the number of transformations of the student ID numbers by preliminarily grouping the test sheets as a preprocessing task.

Experiment 1

Purpose

We investigated the relationship between the task performance and the task complexity, i.e., the task completion time and the number of errors respectively, when preprocessing is conducted or not.

Method

Participants Forty-six university students participated in this experiment.

Material A set of fifty test sheets made from A4 sized paper was prepared for each trial. Three trials were performed and a different set was used in each trial. All three sets were controlled using the number of times, and the order in which the operations of carrying and borrowing were required for the calculation to transform the student ID numbers. The tally sheet was made of A3 sized paper. A scenario with two grades, two majors, and five courses were conjectured with twenty students belonging to each course. Therefore, 400 empty cells ($=2\times 2\times 5\times 20$) were placed on the tally sheet. By transcribing all the scores to the tally sheet, fifty cells out of the 400 blank spaces had to be filled in. A desk with space large enough to accommodate ten A4 sized papers was used for preprocessing. Also, another desk was used for primary processing, that is, transcribing the scores to the tally sheet with a pencil.

Factorial design The experiment had a three-factor mixed design. The factors were: (1) Task complexity (high and low) between participants; (2) Preprocessing (preprocessing and no preprocessing) between participants; (3) Trial (1, 2, and 3) within participants.

Procedure In order to confirm participants' ability to calculate, they were required to solve computational problems that consisted of a total of 25 addition and multiplication problems. The main task was conducted three times with different sets of the test sheets and the tally sheets. At the beginning of each trial, the participants were informed of their task completion time and the number of errors in the previous trial as feedback. As a preprocessing condition, the participants had chosen a particular way of grouping the test sheets in the first trial and were instructed to rearrange them in the same way throughout the three trials.

Result

In order to maintain homogeneity of the participants' calculation ability, two participants whose computational time in the calculation problems fell outside 2 SD from the mean computational time for each condition were eliminated from the analysis. In addition, it was assumed that the participants who made too many errors in the task could not conduct the task appropriately, therefore three participants whose mean number of errors throughout the three trials fell outside 2 SD from the mean number of errors in each condition were eliminated from the analysis. Moreover, one participant who violated the instructions, i.e., conducted the transforming calculation on the desk space for preprocessing, was eliminated from the analysis. In the following experiments, the identical criteria were used for selecting appropriate participants. As a result, the performance of forty participants, of whom ten were assigned to each condition, was analyzed.

There was no significant difference in performing the calculation problems between the four conditions ($F(3,36) = .07, n.s.$). Therefore, the calculation abilities of the participants among the four conditions were considered equivalent.

Task completion time On the task completion time, a 2 (Task complexity: high/low) $\times$ 2 (Preprocessing: preprocessing/no preprocessing) $\times$ 3 (Trial) ANOVA was conducted. As a result, there was no significant three-way interaction ($F(2,72) = 2.17, n.s.$). There was a significant two-way interaction between task complexity and preprocessing ($F(1,36) = 9.80, p < .005$). There was neither significant two-way interactions between task complexity and trial

($F(2,72) = 1.83, n.s.$) nor between preprocessing and trial ($F(2,72) = .46, n.s.$). Figure 3 illustrates the mean task completion time in Experiment 1 based on the basic concept depicted in Figure 1. In Figure 3, the preprocessing time was measured from the time when the test sheets were put on the desk space for grouping (preprocessing) until they were lifted up for transcribing the scores to the tally sheet (primary processing).

Next, we conducted a simple main effect test on the preprocessing factor. As a result, (1) in the high task complexity condition, there was a marginally significant difference showing that the task completion time was faster in the preprocessing condition than in the no preprocessing condition ($F(1,36) = 3.19, p < .10$), whereas (2) in the low task complexity condition, it was significantly faster in the no preprocessing condition than in the preprocessing condition ($F(1,36) = 6.98, p < .05$).

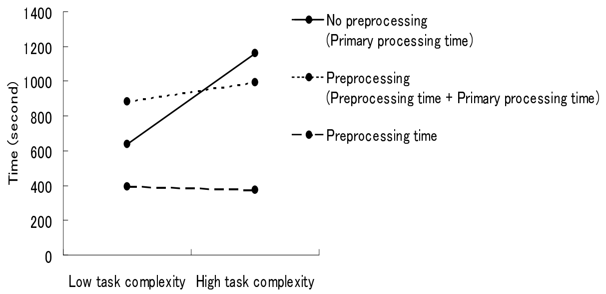

Figure 3: Task completion time in Experiment 1 represented by the basic concept

Number of errors We defined a transcribing error as being a transcription of an incorrect score or a transcription to an inappropriate cell. On the number of errors, a 2 (Task complexity: high/ low) $\times$ 2 (Preprocessing: preprocessing/no preprocessing) $\times$ 3 (Trial) ANOVA was conducted. As a result, there was no significant three-way interaction ($F(2,72) = .61, n.s.$). There was a significant two-way interaction between task complexity and preprocessing ($F(1,36) = 4.37, p < .05$) and a marginally significant interaction between task complexity and trial ($F(2,72) = 2.56, p < .10$). There was no significant interaction between preprocessing and trial ($F(2,72) = 1.98, n.s.$).

Next, we conducted a simple main effect test on the preprocessing factor. As a result, (1) in the high task complexity condition, the number of errors was significantly smaller in the preprocessing condition than in the no preprocessing condition ($F(1,36) = 11.12, p < .005$), whereas (2) in the low task complexity condition, there was no significant difference between the preprocessing and no preprocessing conditions ($F(1,36) = .14, n.s.$).

Discussion

As a result of Experiment 1, it is revealed that conducting preprocessing is effective for the high complexity task, and contrarily, not conducting preprocessing is effective for the low complexity task. These results proved that our transcribing task is an appropriate task for embodying a trade-off between preprocessing and primary processing.

In the following Experiment 2, using the same task, we investigated whether people could adaptively estimate the utility of preprocessing and take rational action depending on the task complexity.

Experiment 2

Purpose

Using the transcribing task, we investigated whether people could adaptively estimate the utility of preprocessing and take rational action depending on the task complexity.

Method

Participants Twenty-seven university students participated in this experiment.

Material Identical materials were used as in Experiment 1.

Factorial design The experiment had a two-factor mixed design. The factors were: (1) Task complexity (high and low) between participants; (2) Trial (1, 2, and 3) within participants.

Procedure Basically an identical procedure to that of Experiment 1 was followed. In Experiment 2, the participants were instructed: "it is allowed to rearrange and group the test sheets, but it is not a requirement to do so." In addition, when the participants chose to conduct preprocessing at the beginning of each trial, they were allowed to decide their own way of rearranging the test sheets.

Result

Three participants were excluded from the analysis based on the same criterion as in Experiment 1. As a result, the performance of twenty-four participants, of whom twelve were assigned to each condition, was analyzed. First, there was no significant difference in performing the calculation problems between the two conditions ($t(22) = .23, n.s.$).

Preprocessing and minimal transformation strategy In Experiment 2, we calculated the ratio of participants conducting preprocessing for each condition. Moreover, there was a rearranging strategy with which the participants could transform the student ID numbers with the minimum number of times in primary processing. This strategy could minimize the cost of primary processing. In particular, this strategy was to group the test sheets according to the categories of Major and Course numbers first. We calculated the ratio of participants using this minimal transformation strategy for each condition. Figure 4 shows the ratio of participants conducting preprocessing and the ratio of participants using the minimal transformation strategy. In the low task complexity condition, the participants gradually learned to conduct preprocessing from the first to third trial. On the other hand, in the high task complexity condition, the participants conducted preprocessing from the first trial. Moreover, the minimal transformation strategy was used more in the high task complexity condition than in the low task complexity condition.

Discussion

As a result of Experiment 2, when the participants were allowed to choose whether to conduct preprocessing or not, the participants conducted ineffective preprocessing in the low complexity condition. Moreover, the minimal transformation

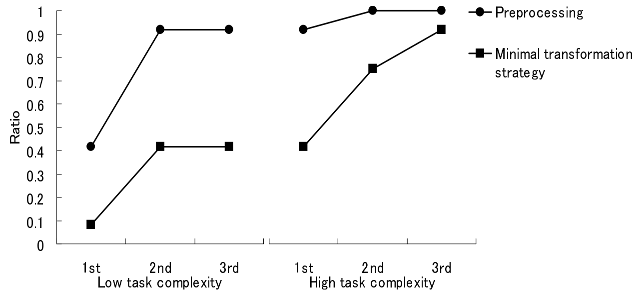

Figure 4: Ratio of participants conducting preprocessing and ratio of participants using minimal transformation strategy in Experiment 2

strategy was used more for the high complexity task than for the low complexity task.

At this point, we have questions. Was it possible the participants were trying to reduce fatigue by grouping the test sheets as a routine work throughout the trials although they realized that conducting preprocessing was ineffective for the low complexity task? Moreover, was it also possible for them to try to reduce the number of errors by grouping the sheets although they noticed that conducting preprocessing increased the task completion time for the low complexity task? To answer these questions, in Experiment 3, we conducted a questionnaire directly asking the participants which makes the task faster and more accurate, preliminarily grouping the test sheets as preprocessing or not. Furthermore, in Experiment 2, at the beginning of each trial, the participants were told the task completion time and the number of errors in the previous trial as feedback. Throughout the trials, the task completion time gradually decreased because of the learning effect. Consequently, the participants might have misunderstood that preprocessing is effective because of the effect of this feedback. Therefore, in Experiment 3, we gave no feedback to the participants.

Experiment 3

Purpose

We replicated Experiment 2 and confirmed whether people could adaptively estimate the utility of preprocessing and take rational action in the low complexity task.

Method

Paticipants Seventeen university students participated in this experiment.

Material Identical materials were used as in Experiment 2.

Procedure Basically an identical procedure to that of Experiment 2 was followed. In Experiment 3, at the beginning of each trial, we gave the participants a questionnaire asking them to estimate the utility of preprocessing for the task completion time and the accuracy. The participants were instructed to choose one out of four choices: (1) preprocessing is effective, (2) no preprocessing is effective, (3) no difference, and (4) impossible to estimate. When the participants chose to conduct preprocessing at the beginning of each trial, they were allowed to decide their own way of rearranging the test sheets. In addition, the participants were instructed to estimate the task completion time and the number of errors after each trial had been completed. They were neither informed of the actual task completion time nor the number of errors as feedback. Moreover, in Experiment 3, we set up the fourth trial in which the participants were not allowed to conduct preprocessing in order to compare the performance with the performance when preprocessing was conducted in the former three trials. Also, the participants were instructed to estimate the task completion time and the number of errors after the fourth trial had been completed.

Result

Two participants were excluded from the analysis based on the same criterion as in Experiment 1. As a result, the performance of fifteen participants was analyzed.

Preprocessing and minimal transformation strategy Figure 5 shows the ratio of participants conducting preprocessing and the ratio of participants using the minimal transformation strategy. The participants gradually learned to conduct preprocessing from the first to third trial. Moreover, the ratio of participants using the minimal transformation strategy was low.

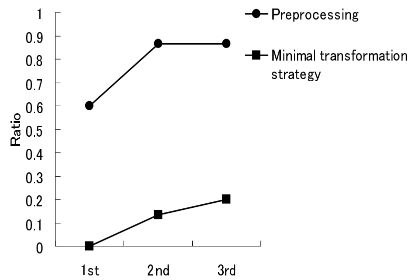

Figure 5: Ratio of participants conducting preprocessing and ratio of participants using minimal transformation strategy in Experiment 3

Estimation of preprocessing utility Figures 6 and 7 show the numbers of choices made in the questionnaire at the beginning of each trial for the task completion time and the accuracy. With each subsequent trial, the participants shifted towards estimating that conducting preprocessing is effective in producing a more rapid performance. They also either estimated that preprocessing was effective or produced no difference in performance accuracy.

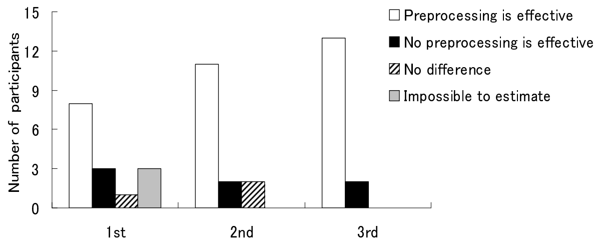

Figure 6: Respondents estimation for task completion time

Actual/ Estimated performance In Experiment 3, almost all participants conducted preprocessing as in Experiment 2. Consequently, we compared the participants' performance when preprocessing was conducted in the first three trials with their performance in the fourth trial where they were not allowed to conduct preprocessing. In particular, the mean

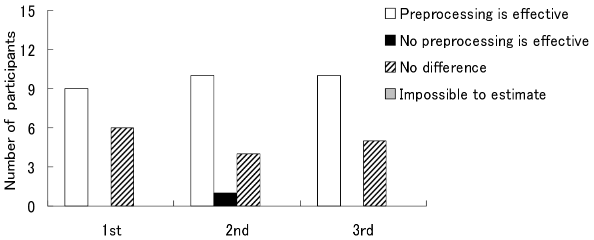

Figure 7: Respondents estimation for accuracy

performance of nine participants, who had conducted preprocessing in all the first three trials, and four participants, who had conducted preprocessing in the second and third trials, was calculated. The result was regarded as the representative performance for when preprocessing was conducted. The performance of these thirteen participants in the fourth trial was regarded as the representative performance for when preprocessing was not conducted. Moreover, we compared the participants estimated performance when preprocessing was conducted in the first three trials with their estimated performance in the fourth trial.

Actual/ Estimated task completion time Figure 8 shows the actual task completion time and the estimated task completion time. We conducted a t-test on the actual task completion time when preprocessing was conducted and when it was not conducted. As a result, the actual task completion time was significantly faster when preprocessing was not conducted than when conducted ($t(12) = 4.49, p < .001$). Moreover, we conducted a t-test on the participants estimated task completion time when preprocessing was conducted and when it was not conducted. As a result, there was a marginally significant difference showing that their estimated time was faster when preprocessing was conducted than when not conducted ($t(12) = 1.89, p < .10$).

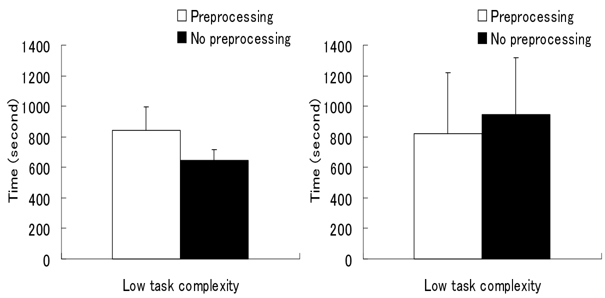

Figure 8: Comparisons of actual task completion time (left) and estimated task completion time (right) when preprocessing was conducted and when it was not conducted

Actual/ Estimated number of errors We conducted t-tests on the actual number of errors and on the participants estimated number of errors when preprocessing was conducted and when it was not. As a result, there was neither significant difference in the actual number of errors ($t(12) = .66, n.s.$) nor in their estimated number of errors ($t(12) = 1.54, n.s.$).

Discussion

First, as a result of Experiment 3, when the participants were allowed to choose whether to conduct preprocessing or not, the participants conducted ineffective preprocessing as in Experiment 2. This result eliminated the possibility that the feedback from their previous performance had encouraged the participants to mistakenly elect to perform preprocessing. Second, the ratio of participants using the minimal transformation strategy was also as low as in Experiment 2. Third, the results of the questionnaire indicated the participants overestimated the utility of preprocessing for the task completion time and the accuracy. This result eliminated the possibility that the participants conducted preprocessing as a strategy for reducing fatigue and reducing the number of errors, because they had reported that conducting preprocessing could reduce the task completion time in the questionnaire. Moreover, we compared the performances when preprocessing was conducted and when it was not conducted in the within-participant experiment. As a result, we confirmed the result was consistent with that of Experiment 1. Contrarily, the participants estimated the actual task completion time faster when preprocessing was conducted than when not conducted. This result is consistent with the result of participants' estimation for the task completion time in the questionnaire given at the beginning of each trial.

General Discussion

The purpose of this study was to investigate whether people can adaptively estimate the utility of preprocessing and take rational action. First, Martin and Schwartz (2009) investigated preprocessing to create representational tools before engaging in a task. However, they evaluated the performances of preprocessing and primary processing separately and did not address the issue of a trade-off between the costs of the two types of processing. They used a learning task to investigate how learning experiences in preprocessing influence the following behavior for learning. In contrast, in this study, we used a problem solving task. In order to investigate the utility of preprocessing, it is crucially important, especially in problem solving tasks, to consider the trade-off between increasing the cost of preprocessing and decreasing the cost of primary processing.

As a result of our experiments, in the low complexity task, preprocessing was aggressively conducted despite it not being effective. In our experimental task, preprocessing was performed with a desk space as an external resource. Brown, Collins, and Duguid (1989a, 1989b) suggested that people actively use external resources at the initial stage as an initial human impulse. In addition, Kirsh (2009) referred to the activity-centric model as an instinctive human behavior of using external resources without thinking. The human nature to instinctively use external resources described in the research of Brown et al. and Kirsh may explain the participants' behavior in our experiments.

Sirouzu, Miyake, and Masukawa (2002) experimentally confirmed such a human nature. They suggested that people actively use external resources as their "proto-plan". In their experiment, the existence of external resources prevented the participants from noticing the availability of usable internal processing. In contrast, in our experiments, the participants conducted preprocessing although they were explicitly offered the choice of using preprocessing or not. Moreover, Sirouzu et al. (2002) stated that the participants divided a single over-all task into multiple simpler sub-tasks using an external resource so that they could visually confirm the completion and the result of each sub-task, and plan the next step. In our experiments, the participants could divide one transcribing task into two different tasks: rearranging the test sheets (preprocessing) and transcribing scores (primary processing). The participants could take advantage of the result of preprocessing, allowing them to conduct primary processing smoothly and easily. It is considered that the effect of such task decomposition causes the overestimation of the utility of preprocessing. Kirsh (1996) explained such human action of task decomposition as a complementary action, which enables the externalization of plans into sub-goals in order to easily achieve a final goal and that this is a central element of human activities.

The result of our experiments about the estimation of a trade-off between two types of processing is not consistent with the findings of Matthew and Anderson (2009). In their experiment, the participants had to choose between solving each problem using a calculator as an external resource or by using mental calculation. The participants were able to make the correct choice whether to use the external resource or not, dynamically and instantly, depending on the task complexity. Matthew and Anderson (2009) used calculation problems that each took around ten seconds to solve. In contrast, in our experiments, we used the transcribing task that took around ten minutes to complete. In order to conduct preprocessing, the participants had to create an additional sub-task as a preliminary task, once stepping away from the primary task, and thus conduct two different types of tasks sequentially. One reason why the participants failed to estimate the costs might be because the cost estimation in our task was much harder than such estimation in the previous study.

Another reason may depend on the participants' time perception. The task completion time in the low complexity task was estimated to be faster when preprocessing was conducted than when not conducted. This trend in estimation was opposite to that of the actual task completion time. In studies of time perception, it has been verified that the more cognitive processing people perform, the less attention they direct to time, so that they underestimate time duration. This phenomenon is explained by the attentional model (Hicks, Miller, & Kinsbourne, 1976; Zakay, 1993). Hicks et al. (1976) investigated the attentional model using a card sorting task. As a result, it was revealed that the more stacks the cards were sorted into, the faster the task completion time was estimated to be, because more cognitive processing was performed as there were more stacks to sort. In our experiments, when preprocessing was conducted, the participants had to sort the test sheets. Therefore, there is a possibility that the participants estimated the task completion time faster when preprocessing was conducted than when not conducted because they performed more cognitive processing when preprocessing was conducted than when it was not conducted in the low complexity task.

Last, the minimal transformation strategy was used more in the high complexity task than in the low complexity task. Cary and Carlson (1999) found that in a situation where high internal costs were demanded, the participants tended to use a strategy to minimize their internal costs. On the other hand, in a situation where low internal costs were demanded, the participants chose a strategy of following structures in the problem, and did not focus on reduction of internal processing. In our experiments, in the high complexity task, the participants rearranged the test sheets according to the categories of Major and Course numbers first. Using this strategy, the participants successfully transformed the student ID numbers for referring to the numbers on the tally sheet using the minimum number of times and minimized internal cost. On the other hand, in the low complexity task, the participants tended to rearrange the test sheets according to the category of Grade number first, affected by the structure of the student ID number in which the first two digits represented the Grade. This meant that they used a strategy to follow the structure of the problem. Our results were consistent with the findings of Cary and Carlson (1999).

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