Prediction of the human response time with the similarity and quantity of information

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Abstract

Memory is one of brain processes that are important when trying to understand how people process information. Although a large number of studies have been made on the human performance, little is known about the similarity effect in human performance. The purpose of this paper is to propose and validate the quantitative and predictive model on the human response time in the user interface with the concept of similarity. However, it is not easy to explain the human performance with only similarity or information amount. We are confronted by two difficulties: making the quantitative model on the human response time with the similarity and validating the proposed model by experimental work. We made the quantitative model based on the Hick’s law and the law of practice. In addition, we validated the model with various experimental conditions by measuring participants’ response time in the environment of computer-based display. Experimental results reveal that the human performance is improved by the user interface’s similarity. We think that the proposed model is useful for the user interface design and evaluation phases.

Keywords: Human response time; Similarity; User interface design/evaluation

1. Introduction

The use of digital systems has been increasing in the complex industry in recent years. The importance of human performance is therefore emphasized for the safety and efficiency of the industries. There are some interfaces in the application of any digital system. Fig. 1 shows that human operator is confronted by a series of interfaces to carry out a task. We should notice that there are some similarities between the interfaces. Although a large number of studies have been made on the human performance, little is known about the similarity effect in human performance. The purpose of this paper is to propose and validate the quantitative and predictive model on the human response time in the user interface with the concept of similarity. We will take an example to show the importance of the similarity. When we are going to the nearest vending machine as Fig. 2 indicates, the reason why we can easily go there is the result of our memory operation.

If we have no memory to go there, we can seek a path to the vending machine by accepting instant information and finally arrive there over a long time. If we have some memory to go there, we can seek the correct path by accepting instant information and comparing it with our memory. Therefore, the similarity of information is an important role of human performance [9]. An understanding of problem solving, categorization, memory retrieval, inductive reasoning, and other cognitive processes requires that we understand how human beings assess similarity [1].

As mentioned above, the similarity can reduce the time of human information processing. The effect of similarity is emphasized by other researchers [2–4]. Only few attempts have so far been made at the quantitative study of the similarity effect on human performance. The Hick’s law and the law of practice may account for the predictive theory of the human performance without the similarity effect [8,10,11]. We made the quantitative model on the human response time with the similarity and the quantity of information by integrating previous two models. The information similarity can be calculated by the similarity theory [1,3]. The information similarity in this paper is determined by the ratio model [3].

Finally, we made a simple experimental work so that we could verify the effect of similarity in visual searching tasks and users had quicker responses than in the case of non-similarity test as the information similarity increased.

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2. Prediction of user response time

2.1. The Information amount and similarity

Entropy has been widely used as a quantitative measure of uncertainty in many fields including thermodynamics, information theory, biology, decision theory, and sociology. In addition, it played a central role in information theory as a measure of information, choice and uncertainty [5]. Hick and Hyman applied information theory to quantify the uncertainty of stimulus events [10,11]. According to the information theory, the average information conveyed by a series of events with different probability is computed by Eq. (1):

\[ H = -\sum_i p_i \log_2 p_i, \]  

where \( \sum_i p_i = 1 \). Eq. (1) is the same as the mathematical definition of entropy in statistical mechanics [6]. \( H \) is always less than or equal to the value when the events with the same probability occur. A human operator has more difficulties in identifying the system states and needs more response time when the system has more states or has states that are more equally probable.

Four major psychological models of similarity are geometric, featural, alignment-based and transformational models. Geometric models have been among the influential approaches to analyze similarity, and are exemplified by multidimensional scaling models [12–14]. In alignment-based models, matching features influence similarity more if they belong to parts that are placed in correspondence, and parts tend to be placed in correspondence if they have many features in common and if they are consistent with other emerging correspondences. The transformational model can be stated that the similarity of two entities is assumed to be inversely proportional to the number of operations required to transform one entity so as to be identical to the other. In this paper, Tversky’s featural model was used to calculate the similarity. We can define the meaning of similarity as the ratio model that is defined by the current state’s information and the previous one’s. The matching function in this study is Eq. (2):

\[ S(A, B) = \frac{f(A \cap B)}{f(A \cap B) + \alpha f(A - B) + \beta f(B - A)} \quad (\alpha, \beta \geq 0) \]  

where \( S(A, B) \) is the ratio of similarity between \( A \) and \( B \) in Fig. 3(a). We focus on the current state in a sequential operation so that either \( f(A - B) \) or \( f(B - A) \) can be eliminated as the right part of Fig. 3(b). The sequential operation means a series of interfaces to carry out a task.

At that point, the set \( A \) means the current interface and set \( B \) means the past interface. Therefore, the similarity matching function can be changed as Eq. (3):

\[ S(A, B) = \frac{f(A \cap B)}{f(A \cap B) + \alpha f(A - B)} \quad (\alpha \geq 0) \]  

Let us assume the denominator as the set \( A \), which means \( \alpha = 1 \). Eq. (3) reduces to Eq. (4):

\[ S(A, B) = \frac{f(A \cap B)}{f(A)}. \]
Eq. (4) means how the ratio of information is the same as the previous states. We can express Eq. (4) as the notation of information amount:

\[ S(A, B) = \frac{H_S}{H}, \]

where \( H \) is the information amount of the interface \( A \) and \( H_s \) is the amount of the same information in the interface \( A \) from the previous interfaces. From now, Eq. (5) is used for the similarity in this study.

### 2.2 Prediction model development

Many researchers have progressively developed the study on the prediction of user response time since 1950s [10,11,15]. Most of studies including this study to predict the user response time have focused on the context around a user. A human operator uses several interfaces to carry out his goal for a task. The elapsed time to complete the task can be predicted by the characteristics of each interface. In this study, we considered two factors of each interface that were the information amount and similarity. We chose Hick’s law and the law of practice as the theoretical basis because those models were developed by empirical methods.

The Hick’s law, which is expressed as Eq. (6), explains that the choice reaction time in visual search task becomes longer as the information amount increases. This can be used to make a time estimate for how long it will take for people to make a decision in using a user interface, such as choosing a menu item or a tool, or selecting an item on a navigation bar [7].

\[ T = A + BH, \]

where \( H \) is the information amount of an interface, \( A \) and \( B \) are regression coefficients.

The law of practice concerns the relationship between expected response time and amount of practice in skill acquisition paradigms. For most of the previous 20 years, researchers have believed that the law of practice was well described by a power function, mainly due to evidences collected by Newell and Rosenbloom [8]. The law of practice explains that if a human operator practices more tasks, the time of task execution should be smaller than previous trial. There are four major equations of this model as expressed in Eqs. (7)–(10). More recently, Heathcote, Brown and Mewhort examined the fit of the power, exponential, generalized power and APEX functions [2]. They found that the exponential function consistently provide a better fit than the power function. Therefore, our study chose the Eq. (7) for applying the law of practice.

\[ T = A_E + B_EQ^{-aN}, \]

\[ T = A_E + B_EN^{-\phi}, \]

\[ T = A_E + B_EQ^{-\phi}E^{-aN}, \]

\[ T = A_E + B_E(N + E)^{-\phi} \]

and where \( N \) indexes practice level, and other constants indicate the regression coefficient. The parameter \( N \) means the practice level of a task. We think that it is similar with the repetition number of a task. In Fig. 4, we may apply Hick’s law for both extreme cases. If the current interface of right part in above figure has the same information amount of the left part, by Hick’s law the expected response time is the same as the left part.

The interaction with some interfaces belongs to a kind of skill acquisition paradigm. Most interfaces during tasks have seldom two extreme cases, but they usually have some similarities between each of them.

Let us think about a simple case with some similarity as shown in Fig. 5. The current interface is partly same as the previous interface. Therefore, there is a similarity between (b) and (a). We can apply the law of practice for the same part.

![Fig. 4. Examples of the expected response time in extreme cases.](image)

![Fig. 5. Simple general case of two serial interfaces.](image)
The expected response time of part (b) may be decreased along path (1), (2), (3) or other shapes as the similarity increases (Fig. 6). We call the decreasing shape as ‘similarity curve’. We cannot know the correct shape of similarity curve but know only its trend. To make a quantitative model we chose path (2), which is the simplest. In this case, the boundary values of the expected response time could be assigned by Hick’s law and the law of practice.

As summarized above things, we can make the following equations:

\[ T_{(b)}(S(b, a), H) = pS(b, a) + q. \]  \hspace{1cm} (13)

Eq. (11) is the same as Eq. (12) with \( 0 \leq S(b, a) \leq 1 \). Eq. (13) represents the path (2) of Fig. 6. We can calculate the values of \( T_{(b)}(1, H) \) and \( T_{(b)}(0, H) \) by Eqs. (6) and (7). Therefore, we find a relationship between the expected response time and information similarity as given in Eq. (14):

\[ T_{(b)}(S(b, a), H) = B_E \left( \frac{1}{e^{a \cdot N_1}} - \frac{1}{e^{a}} \right) S(b, a) + (A + BH). \]  \hspace{1cm} (14)

where \( T_{(b)} \) is the expected response time, \( B_E \) indicates the effect of the law of practice and others indicates the previous explanations. We can expand the Eq. (14) to the most general case that we usually confront to complete a task as shown in Figs. 7 and 8. Fig. 7 shows the practice level of each information in the current interface. The reaction time will be decreased as the practice level is increased. When the current interface has several same parts, each part may have the different practice level. The value of ‘m’ in the Fig. 8 refers to the number of same parts. Each same part has its own practice level and same information amount. We can express those factors as Eq. (15):

\[ \tilde{S} = \left( S(b, a)_1, \ldots, S(b, a)_m \right) \tilde{B}_S \]

\[ = \left( B_E \left( \frac{1}{e^{a \cdot N_1}} - \frac{1}{e^{a}} \right) \right) \ldots B_E \left( \frac{1}{e^{a \cdot N_m}} - \frac{1}{e^{a}} \right) \]  \hspace{1cm} (15)

where \( N_i \) indicates the practice level at part \( i \). If the Eq. (15) applies to the Eq. (14), we can get the following Eq. (16):

\[ T_{(b)}(\tilde{S}, \tilde{B}_S, H) = \tilde{B}_S \tilde{S}^T + (A + BH). \]  \hspace{1cm} (16)

This model can cover the range from Hick’s law to the law of practice. We can predict the user response time by information amount and similarity of a set of interfaces. The regression coefficients should be found by the empirical methods.

3. Experimental works

We made a simple window-based GUI for visual search tasks as shown in Fig. 9(a), which consists of center text box and circular text boxes. This display arrangement leads to reduce the letter-position effect in the navigation of the user. Our task is that if human operator receives a command message with sound through the GUI, he should quickly find the correct display item and push the button. The elapsed time from showing a notification message to push the button is the measured variable in this experiment. The experiment factors are the information amount and the degree of similarity as shown in Table 1. These factors were implemented by Fig. 9(b). We executed two experiments: one is to get the regression coefficients of Hick’s law and the law of practice and the other is to verify the proposed model with those
regression coefficients and the results of this experiment. 20 users participated in the experiment.

Test procedure and conditions:

- Explain the experiment procedure to participants
- Repeat the following procedures with increasing information amount and similarity until final experimental condition
  - 1st Stage: all surrounding characters are new
- The character at the center line on the monitor is the target which testers should find it around circular arrangement
If participants see the target with ‘ding’ sound, they should click the same character on circular characters as soon as possible. If then, participants wait for their action during 2500 ms.

- 2nd Stage: some of characters are new and others are same at the 1st Stage
- The character at the center line on the monitor is the target which testers should find it around circular arrangement
- If participants see the target with ‘ding’ sound, they should click the same character on circular characters as soon as possible
- If then, participants wait for their action during 2500 ms.

3.1. Experiments of reference theories

The left graph of Fig. 10 shows the experimental result and the linear regression result. The linear regression result is well fit for Hick’s law. The right graph of Fig. 10 tells us that the law of practice is of practical use for the human performance with the task repetition. The red line in the right graph is the exponential decay regression result.

3.2. Experiment of verifying proposed model

The line with rectangular point in Fig. 11 is 1st stage experimental result without the similarity. The line with circular point in Fig. 11 is the average value of 2nd stage experimental result with the similarity on each information amount. The line with triangular point in Fig. 11 is the trimmed data of 2nd stage experimental result by considering extremely large and small measurements. Therefore, we can easily find the enhancement of human performance by the similarity. Fig. 12 is the user response time on each similarity without the effect of information amount. The linear regression was performed by the basis of Eq. (14). We can get the coefficients in Eq. (14) by Figs. 11 and 12 as follows:

![Fig. 10. Test results of Hick’s law (left) and the law of practice (right).]

![Fig. 11. Test results of the reaction time on each similarity.]

Table 1
Test matrix of experiments

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<th>No. of same information in total information</th>
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<td>11</td>
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<td>13</td>
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</tr>
</tbody>
</table>

Equation: $y = A_1 \exp(-x/\lambda) + y_0$
Weighing: $y$
Statistical $\chi^2/\text{DoF} = 5.04139$
$R^2 = 0.77069$
$y_0 = 3025.34752 \quad 4465.21039$
$A_1 = -1671.68182 \quad 4380.46514$
$\lambda = -46.83577 \quad 58.699$

![Table 1: Test matrix of experiments]

![Fig. 12. User response time on each similarity without the effect of information amount.]

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We can predict the user response time on each similarity by Eq. (14). The line with reversed-triangular point in Fig. 13 means the expected value on human response time by our model and the line with triangular point means the measure value on human response time by our experiments. The errors of the expected values were based on each personal characteristic. We set the delayed time (2500 ms) between the moment of finishing a action order and the moment of initiating a display because. Therefore, the delayed time means the relaxation of test participants.

4. Conclusions

Proposed model has been developed for the quantitative and mathematical prediction method on the expected response time in sequential operations. This model also represents the unified equation of both Hick’s law and the law of practice using the information similarity. As designers or evaluators in human computer interaction (HCI) field use this proposed model, they may make efficient and effective interfaces. Our emphasis in this study is that we should consider the effect of similarity between interfaces or tasks to design them for the better human performance. We think that the similarity curve that is proposed in this study indicates the nature of human. However, this study should refine the basic logics and the approach methods by reviewing with many researchers. In addition, many experimental works are needed for collecting reliable data to use some regression coefficients and to find out the shape of similarity curves on each person.

References