RUNNING HEAD: PREDICTING OBJECT ASSEMBLY DIFFICULTY

IDENTIFYING THE TASK VARIABLES THAT PREDICT OBJECT ASSEMBLY DIFFICULTY

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ABSTRACT

Objective: We investigated the physical attributes of an object that influence the difficulty of its assembly. Identifying attributes that contribute to assembly difficulty will provide a method for predicting assembly complexity.

Background: Despite object assembly being a widespread task there has been insufficient research into information processing and cognition during assembly. The lack of research means that we are unaware of the variables that affect the performance of procedural assembly tasks with illustration only instructions.

Method: In Experiment 1, seven physical characteristics (task variables) of assembly objects were systematically varied in a balanced fractional factorial & orthogonal design to create 16 abstract assemblies which were assembled by 12 participants (6 males and 6 females aged 18 to 56). A second experiment (20 participants, 8 males and 12 females aged 18 to 52) involved scaled-down models of 8 real-world assemblies.

Results: A clear relationship between the task variables and assembly difficulty was found in both studies and the regression model from the first experiment was able to predict the assembly difficulty timings in Experiment 2.

Conclusion: The proposed task variables are associated with assembly difficulty and the regression analysis has shown four of the task variables to be significant predictors of difficulty.

Application: Applications of this research include the use of the regression model as a tool to evaluate the difficulty of assemblies or assembly steps defined by instructions. The task variables can also be used to produce guidelines to ensure assemblies or assembly steps are manageable.

INTRODUCTION

Ready-to-assemble (RTA), flat-pack or self-assembly products have become increasingly common as they offer good value by reducing transport and labor costs (Sundarraj, Madan & Bramorski, 1997). Despite findings that the inclusion of textual information alongside diagrams is beneficial for accuracy (e.g. Booher, 1975) it is common to find illustration-only instructions supplied with self-assembly products as they reduce the costs of translating instructions for international markets (Zanon, 2002). It is now common for novices to undertake one-off (as opposed to production line assembly) object assembly tasks at home where inadequate assembly can cause injury (Page, Lee, Grant, Clift & Bird, 1996). Due to the lack of research in this area there is only anecdotal evidence (e.g., Margolis & Seaton, 1996) that people often find assembling self-assembly products difficult.

It has been noted that there has been insufficient research regarding diagrams in assembly (Novick & Morse, 2000), information processing in assembly (Prabhu, Helander & Shalin, 1995) and human cognition in assembly performance (Shalin, Prabhu & Helander, 1996). Morrell and Park (1993) also noted that little is known about the effects of illustrations on the performance of assembly tasks, concluding that unknown variables play extremely important roles in the performance of procedural assembly tasks with illustration only instructions and that these should be identified.

Morrell and Park (1993) found that individual differences in age and working memory measures accounted for a low level of variance in assembly time ($R^2 = 0.41$). Clearly measures of individual differences cannot solely explain the variance produced by the differing complexity of the assemblies. Richardson, Jones and Torrance (2004) argued that it is the physical characteristics or features of an assembly task that fundamentally define an assembly’s complexity. Further, these characteristics define the instructions and although instruction design is important there is a need to consider the root of assembly complexity. Richardson et al. identified seven physical characteristics, referred to as task variables, which were found to be significant predictors of perceived assembly task complexity. The present research will demonstrate that the task variables also predict assembly task difficulty when full construction of assemblies is involved. As well as leading to a greater understanding of what factors impact on assembly difficulty, the task variables allow objects and their step-by-step instructions to be evaluated and assembly difficulty, either as a whole or individual steps defined by the instructions, to be predicted. This will provide a tool for checking that assembly steps defined by the instructions and whole assemblies are not too onerous before the self-assembly product goes for more expensive user evaluation or to the market place.

First, the literature related to the area is introduced. Second, an outline of the proposed task variables will illustrate factors that are hypothesized to affect assembly task difficulty.

Object Assembly Literature

Rather than aiming to understand the fundamental sources of complexity within assembly objects, existing ergonomics research into assembly is concerned with production line environments and issues relating to workers health and productivity. Unfortunately there is little in this literature that informs the current research.

Design for Assembly (DFA): There are a number of DFA techniques including those of Hitachi (Japan), Lucas (UK) and Boothroyd-Dewhurst (USA). These techniques are evaluative methods concerned with minimizing the cost of assembly on assembly lines and use their own synthetic data to provide guidelines and metrics to improve the design in its ability to be assembled (Boothroyd, 1983). Some of the issues raised are irrelevant to one-off assemblies and the synthetic data they are based on is likely to be gained from a production environment once the task has been learnt and is biased towards motor activity rather than cognition.

Predictive Models of Assembly Time: Predetermined Motion Time Systems that focus on external motor activities have typically been used to predict assembly time, with the prediction of assembly time from an internal cognitive and perceptual perspective receiving very little attention. Fish, Drury and Helander (1997) found that a NGOMSLA model could be used to predict error-free assembly time. However, the model is assembly and operator specific and therefore unable to provide generic predictions of assembly performance based upon characteristics of the assembly object, and is therefore not a practical tool for predictions of assembly performance in one-off object assembly.

Cognition and Assembly: There has been little analysis of the role of human cognition in assembly performance (Shalin et al., 1996). The primary aim of the present research is to identify the characteristics of an assembly object that impact on cognition and affect assembly complexity. Therefore, an overview of cognition during assembly is required in order to identify the assembly task characteristics that affect assembly task complexity. Assembly depends upon spatial problem solving ability (Pillay, 1997) and requires people to construct mental representations in order to comprehend and manipulate the spatial information (Cooper, 1988). These mental representations will place a demand on cognitive resources. Cognitive Load Theory (Sweller, 1988) deals with the interaction of cognitive structures and information and its implications. It is based upon the limitations of the human information processing system, such as Working Memory (WM) capacity. Cognitive load refers to the amount of processing being performed and the inherent complexity of the assembly may cause cognitive load (Pillay, 1997).

Assembly Object Characteristics: The present research aims to identify the characteristics of the assembly object that impact on assembly complexity. It must be stressed that characteristics of an assembly that can be theoretically justified and linked to cognition are being investigated. Physical characteristics such as size and weight will affect assembly performance, but this is because of the physical difficulty of manipulating the object during the assembly procedure.

Studying the characteristics of the assembly object has received very limited attention. Madan, Bramorski and Sundarraj (1995) hypothesized that the difficulty in identifying parts can be reduced by packaging components in groups according to the order of assembly. Using an abstract 64-component part LEGO assembly, they divided component parts into 1, 2, 4, 8, or 12 bags based on order of assembly. Assembly time was reduced as the number of bags increased until 12 bags were used, at which point assembly time increased and the benefit of component grouping was lost. This research demonstrates that the selection of components is a characteristic of an object assembly that affects assembly difficulty.

Baggett and Ehrenfeucht (1988) used sequence information from the order of requests for pieces in an assembly task to determine how assemblies are conceptualized into groups of sub-assemblies. Participants completed an 80 piece assembly using a pre-built assembly as a guide, and asked the experimenter for pieces as they built the assembly. A cluster analysis showed that when building an object people conceptualize the object as a hierarchy of sub-assemblies and then group requests for components according to this conceptualization. A second experiment, using the typical and atypical conceptualizations gained from the first experiment, showed that participants performed much better when the conceptualizations of the instructions conformed to typical rather than atypical divisions of sub-assemblies. The results show that the physical characteristics of an object go beyond simple measures, with participants using complex conceptualizations that interact with assembly performance.

These studies show that the characteristics of an assembly object, namely grouping of components and component selection, impact on assembly difficulty. However, Morrell and Park (1993) concluded that there are several unknown factors that play important roles in object assembly difficulty. Richardson et al. (2004) identified seven task variables that were hypothesized to predict assembly complexity, and systematically varied them in 16 assemblies. Participants made judgments based on the assembly instructions, with viewing time being recorded. There was a clear relationship between the task variables and the time taken to view the instructions. The present research is required to investigate the relationship of the identified task variables to assembly difficulty when the objects are physically assembled. Finding a clear relationship between the task variables and assembly difficulty would provide a significant step towards identifying further factors that influence assembly difficulty and provides a method for predicting assembly complexity and difficulty.

Assembly Task Variable Identification and Definition

To identify the fundamental steps required during assembly, task description was performed using Hierarchical Task Analysis (HTA). HTA begins with a primary goal that is redescribed into a series of more detailed operations and is well documented (Shepherd, 1998). In the present research the Task Variables identified are applied to a range of assemblies so a generic task analysis that describes a range of assembly tasks was performed. The subordinate operations of object assembly were initially stated and observed in a single assembly task. An iterative process of redescription produced five fundamental sub-operations of a typical assembly which are performed a number of times depending upon the number of components. Refer to instructions and initial component sort; Select components and fastenings for assembly; Orientate components; Relative positioning of components; Fasten components. To ensure the HTA provided data applicable to a variety of assemblies, the adequacy of the redescription was confirmed by comparing it to a variety of sets of assembly instructions for a range of self-assembly products.

The sub-operations identified in the HTA were mapped on to physical characteristics of the assembly which can be hypothesized to have an impact on cognition and therefore affect assembly complexity. The sub-operations of the HTA are now taken in order and related to proposed task variables.

Refer To Instructions and Initial Component Sort (HTA Step 1): This sub-operation mainly relates to the observed behavior associated with instruction comprehension and so does not directly map on to a particular assembly characteristic. However, similarly to the select component sub-operation below, the initial component sort can also be related to the work of Madan et al. (1995). There is theoretical justification for a task variable related to instruction comprehension as groups of components often form identifiable parts and people think about objects in terms of their parts, those that are perceptually salient and functionally significant (Tversky, 2003). It is argued that these parts may allow memory conservation functions through chunking. Further, Baggett and Ehrenfeucht (1988) demonstrated that it is advantageous for the instructions to match the conceptualization presented in the instructions. It is therefore proposed that the structure of the assembly may relate to the process and performance of instruction comprehension and a task variable named ‘Component Groups’ is proposed. A component group is a combination of components that are clearly separated from other groups of components in the assembly. Connecting parts that could be cut in a single plane to reveal the component groups should physically separate the component groups in the assembly step or task being evaluated.

Select Components and Fastenings for Assembly (HTA Step 2): Selection of components for the next assembly procedure, or when using step-by-step instructions, the next assembly step, is affected by the number of components to choose from. The number of elements to be searched has a dominant effect on search time (Drury & Clement, 1978), so the number of components available for selection may impact on cognition and assembly complexity. Therefore a task variable named ‘Selections’ is proposed and defined as the total number of components available to select from at the start the assembly step or task being evaluated.

Orientate Components (HTA Step 3): Shalin et al. (1996) showed how the orientation of the product is critical in component alignment and task completion. Orientation could well involve three-dimensional mental representations that require time, effort and processing resources (Cooper, 1988). Such spatial orientation and manipulation is sensitive to the complexity or amount of information processed simultaneously (Denis, 1991). However, the orientation of the component to allow positioning is affected by the characteristics of the component, (e.g., a symmetrical component can be correctly placed in more than one orientation). Therefore, decisions relating to orientation are related to the number of symmetrical planes of the component. With a higher level of symmetrical planes fewer rotations are required until the correct orientation is found. A task variable named ‘Symmetrical Planes’ is therefore proposed and defined as the mean number of symmetrical planes measured in three planes, X, Y and Z per component in the assembly step or task being evaluated.

Relative Positioning of Components (HTA Step 4): The relative positioning of a component is guided by the fastening points that provide cues or options for positioning of components. The greater the number of possible fastening points the greater the number of possibilities for a components position. This relates to Hick’s law which states that reaction time increases as a logarithmic function of the number of alternatives (Hick, 1952). Further, Shalin et al. (1996) showed how the choice of assembly procedures available at each step increases assembly difficulty. The assembly alternatives available will relate to the number of fastening points available, which may impact on cognition and assembly complexity. Therefore a task variable named ‘Fastening Points’ is proposed. In many circumstances this task variable may be the same as the number of fastenings, although when an assembly is broken into steps, initial steps may have few fastenings, but many remaining fastening points. The number of fastening points are likely to increase in line with the number of components, so the mean number of fastening points available per component in the assembly step or task being evaluated was used.

Fasten Components (HTA Step 5): Fastening of components is required to complete assemblies. Marcus, Cooper and Sweller (1996) found that a high number of connections between components inferred from the instructions and held in WM led to a high cognitive load and hence poor performance. The number of fastenings increases as number of connections between components increases, which may impact on cognition and assembly complexity. Therefore, a task variable named ‘Fastenings’ is proposed and defined as the total number of fastenings required in the assembly step or task being evaluated.

Task Variables Related to Sub-operation Performance: If an assembly procedure is repeated during assembly with the same components it’s sub-operations will have been performed before, so the assembly procedures are likely to become easier to perform because processing resources are reduced (Cooper, 1988). A task variable named ‘Novel Assemblies’ is therefore proposed and defined as the number of unique assemblies in the assembly step or task being evaluated.

A final more general issue related to the performance of the sub-operations identified in the HTA is the number of components in an assembly. The number of components could be an issue in assembly complexity as too many elements of information can overwhelm WM (Kalyuga, Chandler & Sweller, 1998). A task variable named ’Components’ is proposed and defined as the number of components added in the assembly step or task being evaluated (excluding fastening devices such as screws, nuts and bolts).

Summary

In the following studies the task variables defined above are systematically varied while holding the mode of task presentation constant (diagrammatic instructions). This will reveal how the task variables relate to assembly difficulty, measured by assembly time (with fastening time removed). The level to which the identified task variables affect difficulty allows assembly difficulty itself to be predicted, providing a practical tool for the evaluation of assemblies. It also allows practical recommendations of task variable levels to ensure complete assemblies or single assembly steps are manageable.

EXPERIMENT 1

The first experiment was designed to examine how each of the proposed task variables related to assembly difficulty when full assembly takes place. Richardson et al. (2004) found that task variable levels could not be controlled adequately in commercial real world assemblies, as the task variables tend to correlate strongly. Furthermore, to provide sufficient independent variability to disambiguate the separate effects of the task variables, and to control collinearity in the regression analysis, orthogonal assembly tasks had to be designed. Sixteen abstract assemblies were developed and are used again in the current study.

Definition of Abstract Assemblies

So that the influence of each task variable could be examined independently of the others, each task variable was assigned a value, either high or low. Using two levels for each task variable produced a total of 128 possible combinations for the seven task variables. A balanced and orthogonal fractional factorial design then took a random sample of 16 combinations while ensuring that no single task variable would correlate with any other. The levels of each task variable for each assembly formed the basis for the development of the 16 abstract assemblies.

Table 1 shows the task variable levels, high or low, that were used to design each assembly. For example, assembly three (see Figure 1) contained: A low number of component parts, a high level of symmetrical planes, a variety of components to create a high number of novel assemblies, a high number of fastenings, a low level of fastening points, a low number of component groups and a high level of selections.

Calculation of task variable levels: An example of how the task variable levels are calculated for an assembly is given below, for the assembly shown in Figure 1 (this assembly is assembly three in Table 1). Note that the numeric values shown in Table 1 are coded as being either high or low based on median splits.

The number of components (excluding fastenings) is given by counting the raw number of components. This results in a level of five for the components task variable in Figure 1.

The number of symmetrical planes is calculated by measuring the mean number of symmetrical planes measured in three planes, X, Y and Z per component. In Figure 1 it can be observed that all five components have two symmetrical planes each. The level of symmetrical planes is (2 + 2 + 2 + 2 + 2 = 10) divided by the number of components (5).

The number of novel assemblies is defined as the number of unique assemblies in the assembly step or task being evaluated. In Figure 1 all of the assembly procedures are unique (none are repeated) and there are four occasions where individual components are combined, therefore the level of novel assemblies is four.

The number of fastenings is a simple count of the fastenings required in the assembly and in Figure 1 equals ten.

The number of fastening points is calculated by dividing the total number of fastening points by the number of components. In Figure 1 from left to right it can be observed that the first component has two possible points where a fastening can be inserted. The second component has three, the third component has five, the fourth component has seven and the fifth component has three fastening points. The total number of fastening points (20) divided by the number of components (5) equals four.

The number of component groups is the number of combinations of components that are clearly separated from other groups of components in the assembly. In Figure 1, there are clearly two groups of components that are physically separated by a single component, so the component groups is two.

The number of selections is the total number of components available to select from at the start the assembly task. This would normally match the number of components, but when the level of selections was high, unneeded components were added to the box of components. For assembly three in Figure 1 eight components were added to the five required.

Insert Table 1 about here

Insert Figure 1 about here

Method

Participants: Six females and six males, age range 18 to 56 years, from a variety of backgrounds. All the participants successfully completed a screening task that involved assembling a number of components to be identical to a completed assembly (instructions were not used, as it was competence in assembly that was being assessed). No potential participants were excluded by the screening task.

Materials: Junior Meccano was used for the assemblies. All components were yellow and all fastenings were black. Some components were pre-constructed using yellow bolts in order to distinguish them and these were considered as single components. Three simple practice assemblies were also designed with 2 or 3 components and 2 to 4 fastenings. An assembly task with 7 components and fastenings was used to screen participants. Digital images of the assembly components were combined to create exploded isometric views of each of the assemblies, in order to create one-step assembly instructions (see Figure 1 for an example).

Procedure: Participants were seated for the initial screening task. They were asked to use the components provided to make an object that is identical to the completed assembly provided (all participants completed the screening task successfully). Participants then proceeded to an observation room containing a PC, monitor and two video cameras. A 30 inch square table in front of the PC provided an assembly area. To the left of the assembly area was a further table with a box containing all the fastenings required. Participants were shown the video cameras. A video camera was placed above the assembly area and used to record hand movements only. A second camera was placed behind and to the right of the participant to observe overall behavior and the state of the display screen. The video images were recorded on a Panasonic video reorder situated in the Video Control Room.

Participants were seated and told that they would be presented with instructions for 3 practice assemblies and 16 further assemblies, and their task was to complete each assembly. Participants were then informed that further instructions would be presented on the PC monitor and that they should follow the prompts on screen. Participants were informed that sometimes more components than needed to complete the assembly would be provided and that while working they should keep the assembly and components on or above the assembly area. Finally, they were told that before each assembly the PC would beep. At this point the investigator would arrive with the relevant box of components. Participants would then press the space bar on the PC keyboard to reveal the instructions and begin the assembly.

The instructions for the 3 practice and 16 full assemblies were presented on a 15" display screen via a program written in Macromedia Authorware running on a Pentium PC. The program presented the 16 assemblies in a random order. The format for each assembly was as follows: before each assembly the PC would beep and indicate an assembly number, at which point the investigator would remove any completed assemblies and bring the relevant box of components for the next assembly; participants would then press the space bar on the PC keyboard to reveal the instructions and begin the assembly; when the participants were satisfied that the assembly was complete they pressed the space bar, which erased the instructions.

Results

Coding: A coding scheme to remove the variability in the total assembly time due to the time spent on fastening procedures was required. The time remaining (‘thinking time’) reflects the time participants had spent viewing the instructions and deciding how to assemble the object. Fastening time was determined by examining two participants’ data in detail. Fastening time began when the component/s were in the final position or ready for assembly. This process could begin with one of several fastening actions: getting bolts, inserting bolts or turning bolts. The fastening process included tightening or component adjustment after fastening and rapid repeat assemblies where there was no identifiable thinking time. Repeat assemblies were defined as consecutive identical assemblies that required minimal orientation or positioning and where the fastening processes flowed into one another without a break. Fastening time also included time spent fetching fastenings. Timing stopped when fastening was complete or fastening actions paused e.g., for checking instructions. During coding the timing was started when instructions first appear on screen and ended when they were erased.

Inter-rater reliability: A random sample of 10 assemblies were taken and coded by a second researcher who was not part of this research project. Thinking time showed a significant correlation with the main coders ($r(8)=0.902$, $p<0.01$).

Table 2 shows the mean total assembly time and coded thinking time for the 16 assemblies. There was a significant correlation between total time and thinking time ($r(190)=0.794$, $p<0.01$).

Insert Table 2 about here

Errors were coded but analysis is not reported, as error rates were low (0.55 errors per assembly). Note that thinking time includes assemblies with errors and that errors were found to account for only a small amount of variance in thinking time.

Relationship of Task Variables to Thinking Time: Thinking time correlated significantly with 6 of the 7 task variables at the $p=0.05$ level, the exception being Component Groups. The thinking time was subsequently transformed for each assembly as it was skewed towards zero, Dependent Variable (DV) = LOG(Thinking time). To examine the relationship between thinking time and the assembly task variables, multiple regression analysis was used. All 192 observations of thinking time for the 16 assemblies were included in the analysis. The independent variables (IVs) or predictors were the seven task variables, entered as continuous measures rather than the high and low values used in the definition process. As there was multiple data for each participant, dummy variables to identify each participant were entered in the first block in order to control for variability due to individual differences (Pedhazur, 1982). The main IVs were then entered.

The between participants dummy variables in model 1 gave R=0.23 and the Adjusted R^2=-0.01. The model including the seven task variables gave R=0.80 and R^{2adj}=0.60 (F(18,173)=16.64, p<0.01), with the R^2 Change figure suggesting that 58.2% of the variance in thinking time was related to some combination of the task variables.

Four of the task variables were found to be significant predictors of thinking time at the p=0.05 level. Standardized regression coefficients for each task variable suggested an increase in thinking time was associated with increases in Novel Assemblies (0.412, $t(173) = 6.76$, $p<0.001$), number of Selections (0.393, $t(173) = 7.54$, $p<0.001$), number of Components (0.129, $t(173) = 2.05$, $p=0.043$) and a decrease in Symmetrical Planes (-0.307, $t(173) = -6.21$, $p<0.001$). Fastening Points (0.101, $t(173) = 1.93$, $p=0.055$) was close to significance, while Component Groups (0.050, $t(173) = 1.01$, $p>0.05$) and Fastenings (-0.057, $t(173) = 0.96$, $p>0.05$) were not significant.

Interaction effects: One can see how much variance in the DV can be explained over and above that explained by the independent IVs by entering all possible paired combinations of task variables into the regression equation after their individual effects as interaction terms. These cross product interaction terms were added to the model to incorporate the joint effect of pairs of task variables over and above their separate effects. Adding the interaction terms produced R^{2adj}=0.86. The interactions explained further variance, but adding interaction terms in this way runs the danger of overfitting the model to what are chance variations in the data. Therefore, the interaction effects may be artifacts of overfitting and are unlikely to be replicable on other datasets.

Prediction of Thinking Time: The significant unstandardized task variable coefficients were used to produce a regression equation for the prediction of thinking time in seconds:

$\text{Thinking Time} = 10^{([0.020\text{Components}] + [-0.117\text{Symmetrical Planes}] + [0.047\text{Novel Assemblies}] + [0.028\text{Selections}] + 1.464)}$

This provides a method for predicting assembly difficulty based upon the values of the task variables inherent in an assembly or assembly step as defined by the instructions. The use of a main effects model with fewer predictors provides a more conservative and robust prediction. A repeat of the previous regression analysis using only the four significant task variables in the regression equation gives almost identical results, R=0.79, R^{2adj}=0.59 (F(15,176)=19.48, p<0.01) and R^2 Change of 57.2%.

The task variable scores for each of the 16 assemblies were entered into the regression equation above to produce predicted thinking times. The predicted times were compared to the mean actual thinking times for each of the 8 assemblies (see Figure 2) showing a strong correlation (r(14) = 0.832, p<0.001)

Insert Figure 2 about here

Discussion

The regression analyses show that the task variables explain the variation in thinking time well. The number of Components Novel Assemblies, Selections and Symmetrical Planes in an assembly were significant predictors of thinking time. Three task variables, fastening points, fastenings and component groups, were not significant predictors. The use of abstract assemblies to systematically vary the task variables has controlled the problems with correlation between the task variables that are likely to occur if real world assemblies are used. The benefit is a robust statistical analysis that reveals how the task variables relate to assembly difficulty and this has provided a reliable regression model that can be used to predict assembly difficulty based on the values of the task variables.

EXPERIMENT 2

The second experiment was designed to replicate experiment 1 while using real world assemblies, a different assembly medium and differing task variable combinations. This approach seeks to confirm that the results of experiment one are not specific to the particular assemblies used, and that they can be applied to real world assemblies. It will also test the regression equation obtained in experiment 1 by using it to predict thinking time for the assemblies in experiment 2. The second study involved full construction of 8 assemblies from illustration only assembly instructions.

Method

Participants: 12 females and 8 males, age range 18 to 52, from a variety of backgrounds.

Insert Table 3 about here

Materials: Eight assemblies of recognizable scaled down real world objects were designed using a different assembly medium (LEGO), see Table 3. As LEGO does not have explicit fastenings (it is push-to-fit) the fastenings task variable was omitted. The eight assemblies were modified based on an iterative process as follows; calculation of task variable levels for each assembly; analysis of correlation between task variables; and modification of assemblies ensuring a range of task variable levels and reduction of any high correlations. Again all assemblies used one color only. In some assemblies lugs were colored to indicate the position of fastenings and therefore reduce fastening points. The symmetry of colored lugs was included in the symmetrical planes measure. A further two, four component practice assemblies were also designed. On completion digital images of the assemblies were combined to create exploded isometric views of the assemblies for use as instructions.

Procedure: The procedure was identical to that used in experiment 1.

Results

Coding: Push-to-fit fastening means that fastening times for assemblies are low, and it is difficult to identify a time for fastening because fastening occurs so quickly. The separation of fastening and thinking times was therefore omitted, with total assembly time used as a measure of thinking time. This is supported by an analysis of timings from a sample of assemblies, as thinking time had a significant strong positive correlation with the total assembly time ($r(5)=0.976$, $p<0.01$). Table 4 shows the mean thinking time for the 8 assemblies.

Insert Table 4 about here

Errors were coded but analysis is not reported, as error rates were low again (0.24 errors per assembly).

Relationship of Task Variables to Thinking Time: Correlation analyses indicated that the thinking time correlated significantly with all of the included task variables at the $p=0.01$ level. The thinking time was subsequently transformed for each assembly as it was skewed towards zero, DV = LOG(Thinking time). A multiple regression analysis was carried out as detailed in experiment 1. The six suitable assembly task variables (Components, Symmetrical Planes, Novel Assemblies, Fastening Points, Component Groups and Selections) were entered. The between participant dummy variables in model 1 gave $R=0.44$ and $R^{2adj}=0.08$. The second model including the six task variables gave $R=0.90$ and $R^{2adj}=0.78$ ($F(25,134)=23.883$, $p<0.001$), with the R^2 Change figure suggesting that 62.5% of the variance in thinking time was related to some combination of the task variables.

Four of the entered task variables were significant predictors of thinking time at the $p=0.05$ level. Standardized regression coefficients for each task variable suggest that an increase in thinking time was associated with an increased number of Components (0.335, $t(134) = 6.57$, $p<0.001$), a higher number of Novel Assemblies (0.300, $t(134) = 5.39$, $p<0.001$), a reduced number of Symmetrical Planes (-0.282, $t(134) = -5.23$, $p<0.001$) and an increased number of Selections (0.246, $t(134) = 3.72$, $p<0.001$). Fastening Points (0.070, $t(134) = 1.14$, $p>0.05$) and Component Groups (0.036, $t(134) = 0.72$, $p>0.05$) were not significant.

Interaction effects: Cross product interaction terms were added to the model as in experiment 1. This did not show any additional benefit of adding the interactions into the model, (R^{2adj} increased by 0.01) suggesting that the interaction effects from experiment 1 may be artifacts of overfitting. The consistency of the main effects reduces the possibility that there are higher-order interactions and differing interaction effects between the two experiments supports concentration on a main effects model. To ensure the high thinking time for the first assembly was not having an undue influence on the results it was omitted from the data set and the above analysis was repeated. It was again found that there is no additional benefit of adding the interactions into the model (R^{2adj} remained the same).

Prediction of Thinking Time: The main focus of this paper is to ascertain task variables that influence assembly difficulty. It is therefore critical that the significant task variables found in experiment 1 can predict thinking time for the assemblies used in experiment two. The task variable scores for each of the 8 assemblies were entered into the regression equation produced in experiment 1 to produce predicted thinking times. The predicted log times were compared to the actual log thinking times for each of the 8 assemblies (see Figure 3) showing a very strong ecological correlation ($r(6) = 0.977$, $p<0.001$) suggesting that the initial equation derived from experiment 1 can be used more generally to assess assembly difficulty. To ensure the thinking time for the first assembly was not having an undue influence on the results it was omitted from the data set and the correlation was repeated, with the correlation again being highly significant ($r(5) = 0.932$, $p<0.001$). A rank order correlation on the full data set confirmed these results ($r_s(6) = 0.929$, $p<0.001$).

Insert Figure 3 about here

The predicted and actual log thinking times can also be transformed into seconds (see Table 5) and a similar, very strong ecological correlation results ($r(6) = 0.991$, $p<0.001$)

Insert Table 5 about here

GENERAL DISCUSSION

The results of the two experiments show a convincing level of consistency. Components, Novel Assemblies, Symmetrical Planes and Selections were significant predictors of assembly difficulty in both studies with very similar standardized coefficients. Both regression models explained the variation in thinking time very well. Furthermore the regression model from the first experiment predicted the results of the second study very well. The replication of the results using different assemblies, construction materials and task variable combinations, together with the success of the main effects regression model is a powerful indication that the approach of using assembly task characteristics to study assembly difficulty is reliable and that the task variables identified are valid. Further the consistency of the main effects and differing interaction effects between the two experiments supports concentration on a main effects model at this stage.

The relationship between the task variables and assembly difficulty shown in the two experiments are psychologically plausible and were generally predicted from the task analysis and definition process which allowed assembly characteristics that impact on cognition to be proposed and quantified in a range of assemblies. Secondly, this process was strongly justified as the task variables were found to account for considerable variation in assembly complexity as measured by thinking time. It can be concluded that Components, Novel Assemblies, Symmetrical Planes and Selections are all contributors to assembly task complexity. It appears that during assembly, the nature of the information (Symmetrical Planes & Novel Assemblies) has been shown to affect assembly complexity and cognitive load, to a level above more simple measures of information (Components & Selections).

The finding that three task variables were not significant predictors of thinking time also has its value. These task variables could be discounted as not being important in the prediction of assembly difficulty. However, they should be included in any future research. It may be that when investigating further types of assembly with a different range of task variable levels the three weak predictors become more important. It could also be that the operational definitions used for the task variables are flawed, particular with regard to the Component Groups task variable. Baggett and Ehrenfeucht (1988) found that assembly structure related to assembly performance, but devising a simple measure for assembly object structure is a challenge.

The task variables proposed can be used to evaluate assembly tasks and instructions. From a theoretical perspective, this allows control and manipulation of individual characteristics of assembly tasks and, by employing predictive models of assembly derived from the current research, matching the complexity of different assemblies. This level of control is necessary when conducting experimental research involving assembly tasks and has not been possible before (Novick & Morse, 2000). There is also clear evidence that the task variable levels that are inherent within an assembly can be used to predict the assembly complexity of that assembly. These predictive models have applied and theoretical applications as they provide a method for the evaluation of assembly task complexity.

Practical applications for this methodology are wide ranging. At one end of the spectrum it adds a simple tool to those involved in Design For Assembly (DFA). Current DFA methods are used to analyze production line assembly tasks and have not considered one off assemblies in the home. Further, current DFA methods are motor based, with little recognition of cognition and complexity. The ability to estimate assembly complexity provides a valuable tool for the evaluation of assemblies and assembly steps defined by instructions. Such a process could inform the design process before the self-assembly product goes for more expensive user evaluation or to the market place. Further, it can inform consumers of RTA products about the likely complexity. Such predictive models can also inform technical writers so that the necessary attention can be given to particularly complex procedures. In such circumstances guidelines derived from predictive models that show how single unit changes in task variable levels affect assembly complexity are perhaps more transparent and accessible.

It cannot be claimed that the present research has produced the definitive predictive model of assembly difficulty. It is advisable that the predictive model should be based on data collected from the type of assembly being predicted and the present research provides a practical methodology. The possibility of collecting data in different situations allows assembly in extreme environments to be studied. For example working underwater places obvious pressures on time, and knowledge of assembly complexity and timing would be advantageous in planning such activities. However, data collected from a range of assembly types raises the prospect of a more generalizable predictive model, although there is a likelihood that there is no single correct approach.

To conclude it has been shown that the proposed task variables are associated with assembly difficulty and the regression analysis has shown four of the task variables to be significant predictors. At least some of the unknown variables that play important roles in the performance of procedural assembly tasks with illustration only instructions suggested by Morrell and Park (1993) have been identified.

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Table 1. Task variable levels that were used to design each assembly.

Table 2. Mean total assembly time and thinking time in seconds for the 16 assemblies.

Table 3. Task variable levels for each assembly.

Table 4. Mean thinking time in seconds for the 8 assemblies.

Table 5. Predicted and actual thinking time in seconds for the eight assemblies.

Figure 1. The instructions for assembly number three.

Figure 2. Actual Log(Thinking time) from experiment 1 versus predicted Log(Thinking time).

Figure 3. Actual Log(Thinking time) from experiment 2 versus predicted Log(Thinking time).

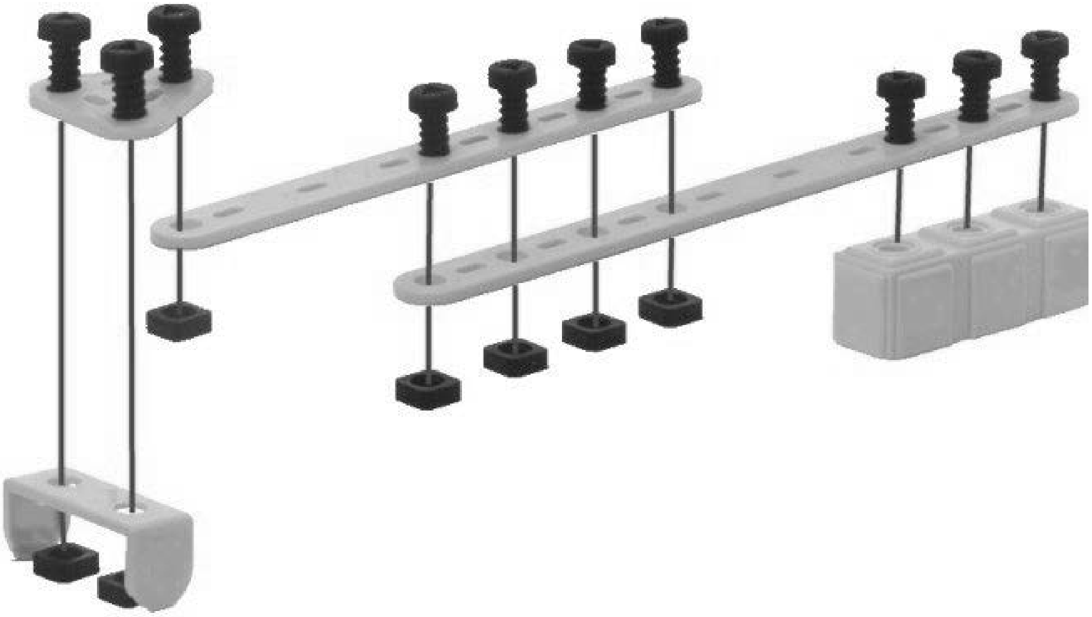
	Components		Symmetrical Planes		Novel Assemblies		Fastenings		Fastening Points		Component Groups		Selections	
ssembly	evel	ctual core	Level	ctual core	evel	ctual core	evel	ctual core	evel	ctual core	evel	ctual core	evel	ctual core

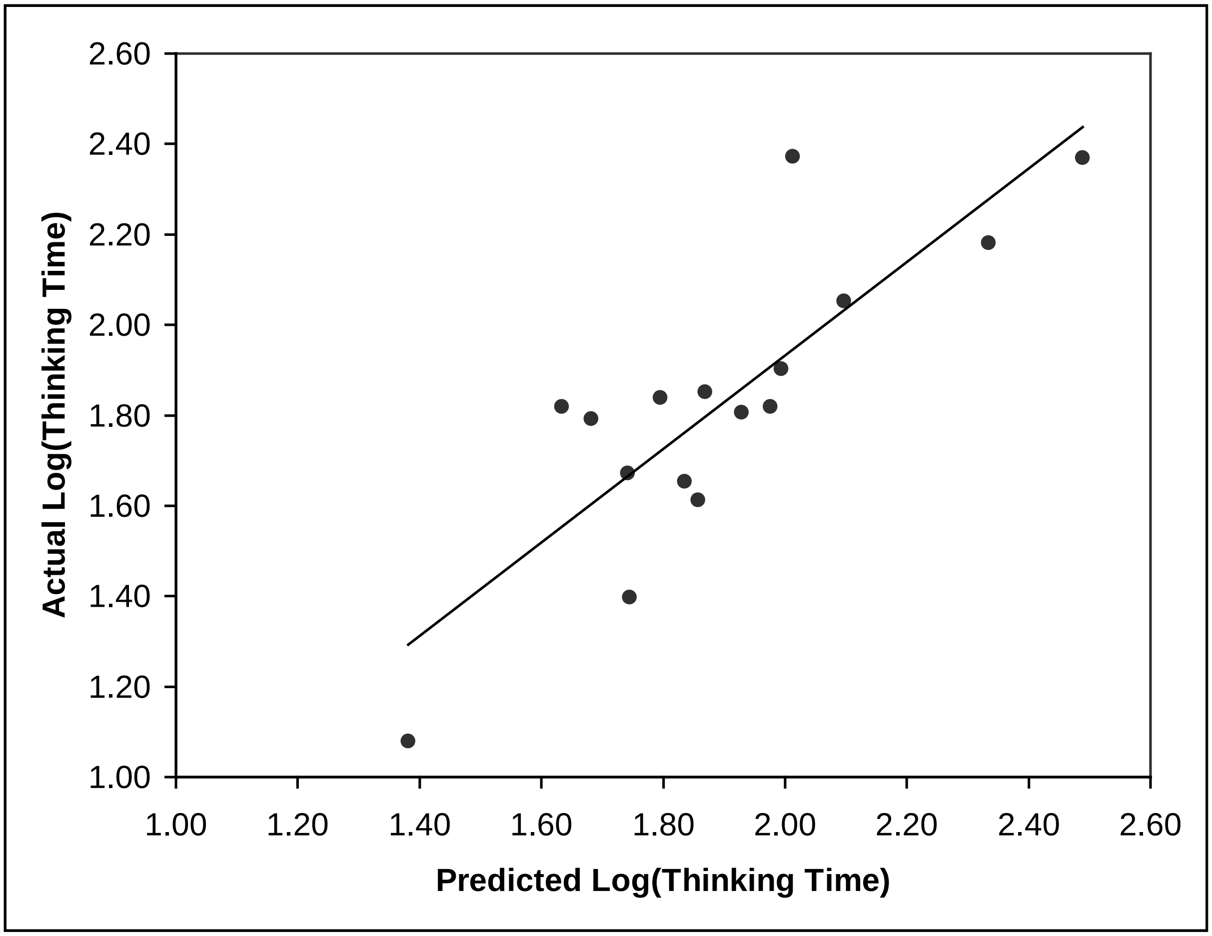
Assembly										0	1	2	3	4	5	6
Total Time	32	14	60	09	1	58	68	86	11	85	90	1	15	82	49	08
SD	15	2	1	0	2	3	7	7	36	6	8		7	2	6	53
Thinking Time	13	4	5	7	1	9	1	6	36	6	2	2	52	5	0	34
SD	8	1	2	3	2	3	1	8	23	4	9		6	6	7	16

Assembly	Components	Symmetrical Planes	Novel Assemblies	Fastening Points	Component Groups	Selections
Side	11	0.36	9	2	1	16
Bed	12	1.83	3	1	3	17
Chai	5	1.8	4	1	3	8
Des	4	0.75	2	1	2	4
L-	8	1.75	6	1	2	8
Shel	7	2	3	2	2	17
Lou	5	0.8	4	2	3	15
Tabl	9	0.67	3	2	2	9
Mea	7.63	1.25	4.25	1.50	2.38	11.7

Assembly	1	2	3	4	5	6	7	8
Mean	242.5	93.8	43.1	39.8	71.9	62.8	90.1	87.9
SD	118.2	31.1	27.4	18.7	26.8	25.7	38.9	34.5

Assembly	1	2	3	4	5	6	7	8
	3	1	5	4	8	9	1	9
Predicted Time	25.7	27.9	8.3	5.9	4.2	7.1	19.8	0.9
Predicted Rank	1	2	7	8	6	4	3	5
	2	9	4	3	7	6	9	8
Actual Times	42.5	3.8	3.1	9.8	1.9	2.8	0.1	7.9
Actual Rank	1	2	7	8	5	6	3	4

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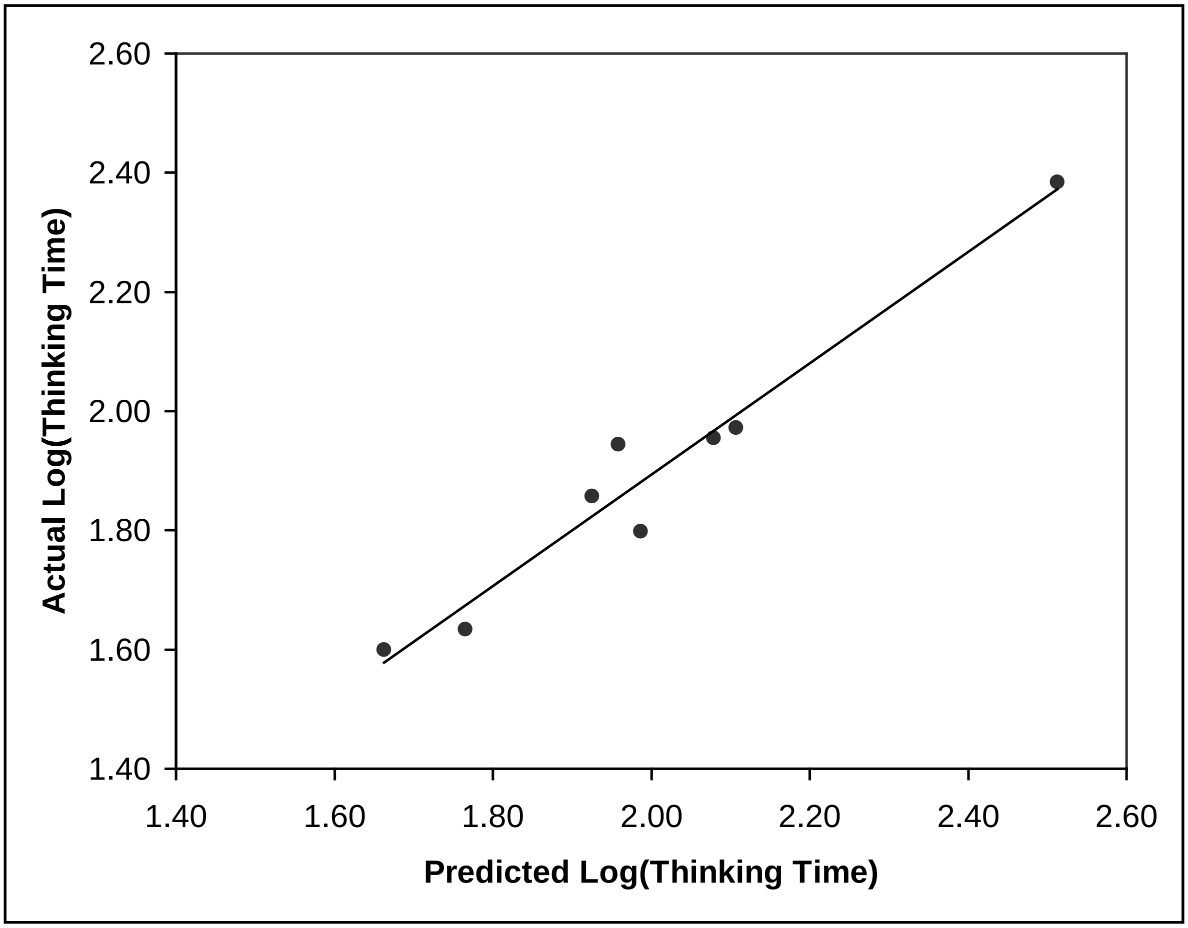
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