In Anthony Jameson, Cécile Paris, and Carlo Tasso (Eds.), *User Modeling: Proceedings of the Sixth International Conference, UM97.* Vienna, New York: Springer Wien New York. © CISM, 1997. Available on−line from http://um.org.

Levels of Expertise and User-Adapted Formats of Instructional Presentations: A Cognitive Load Approach

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Abstract. This paper investigates interactions between user expertise and formats of instructional presentations. A cognitive load approach assumes that information presentation should be structured to eliminate any avoidable load on working memory. The level of learner expertise is a major factor determining intelligibility of information for a user. A diagram might not be intelligible in isolation for less experienced users and so require additional textual explanations. Physical integration (e.g., using spatial grouping or colour coding) of the text and diagram can reduce split attention and an unnecessary working memory load. The same diagram may be understandable for more experienced users. Eliminating redundancy may be the best way to reduce cognitive load in this situation. A series of experiments using instructions in elementary electrical engineering demonstrated the alterations in optimal instructional designs with the development of user expertise.

1 Introduction

An instructional message presented to users on a computer screen usually consists of multiple sources of information (e.g., diagrams, charts, illustrations or a variety of concepts embedded in text). The way this information is structured by designers can have substantial effects on the learnability of material. This paper investigates consequences of users' differing levels of expertise on optimal formats of instructional presentations from a cognitive load perspective.

We have known for some time that processing of information occurs within a limited working memory (Miller, 1956). Only a few items or elements of information can be handled in working memory at any time. Too many elements may overwhelm working memory decreasing the effectiveness of a presentation. An element is anything that has been learned and is handled as a single entity in working memory. Thus a simple algebraic expression (e.g. a/b = ac/bc), for a person familiar with basic algebra, will be processed as a single element easily handled by working memory. However, without this experience the formula will appear as a collection of individual symbols that may be much more difficult for limited working memory to process. It must be noted

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[*] The work reported in this paper was supported by grants from the Australian Research Council and Australian National Training Authority. The authors wish to thank Bryan Jones, Richard Winter and the training team from Email Ltd for their ongoing collaboration and support.

that while the number of elements that can be processed by working memory is limited, the amount of information that can be processed has no known limits because theoretically, any entity incorporating any amount of information can be handled as a single element. Thus a large amount of information may be processed by working memory while dealing with no more than two or three elements.

An unlimited number of elements can be held in long-term memory in the form of hierarchically organised schemas. A schema is defined as a cognitive construct that permits us to treat multiple elements of information as a single element categorised according to the manner in which it will be used. Schemas are stored in long-term memory and can be transferred to working memory as elements to be processed. Because there may be no limit to the size of these schemas, they permit the processing of the information-rich elements in working memory referred to above.

Automation similarly reduces working memory load. Schemas are stored in long-term memory with varying degrees of automaticity. If a schema can be brought into working memory in automated form, it will make limited demands on working memory resources, leaving more resources to, for example, search for a possible problem solution.

Cognitive load theory, incorporating this architecture, has been used to design a variety of instructional presentations both in computer- and paper-based forms (see, e.g., Sweller, 1994, for a recent summary). Most information can be presented in several ways and in the past most instructional design has proceeded without explicit consideration of the limitations of working memory. In contrast, cognitive load theory places a primary emphasis on limited working memory. The theory assumes that information presented to learners and the activities required of them should be structured to eliminate any avoidable load on working memory and to maximise schema acquisition. Two techniques are of relevance to the experiments of this paper.

The split-attention effect. Many instructional presentations include multiple sources of information directed to users for whom one or more sources of information are unintelligible in isolation. Understanding can be derived only by mentally integrating the various sources of information. A geometric proof consisting of a diagram and associated statements provides an example. Neither the diagram nor the statements are likely to be intelligible unless they are mentally integrated. The act of mental integration is cognitively demanding and required purely because of the traditional manner in which geometric proofs or examples are presented. If, rather than using a split-source format with the diagram and statements presented in two discrete, separated modules, the two sources of information are physically integrated, the need for mental integration is reduced. This might be expected to reduce an unnecessary working memory load, freeing resources for schema acquisition and automation. A comparison between split-source and integrated formats has indicated superiority of the integrated format, demonstrating the split-attention effect (see Chandler and Sweller, 1992; 1996).

The redundancy effect. Rather than having multiple sources of information that are unintelligible in isolation, an instructional presentation also can consist of several sources of information, each of which is self-contained and can be understood in its own right. To the extent that the sources of information cover the same area, they are redundant. A diagram associated with text that merely redescribes the diagram is an example. Findings indicate that eliminating redundancy is the best way to reduce cognitive load. When dealing with a diagram and redundant text that describes the diagram, the text should be eliminated rather than integrated with the diagram, because requiring learners to process the text imposes an unnecessary cognitive load. The redundancy effect is demonstrated when performance obtained in a condition in which redundant material is eliminated proves to be superior to a condition including this material (Chandler and Sweller, 1991, 1996; Sweller and Chandler, 1994).

Whether a source of information is intelligible in isolation depends only partly on the nature of the information. It also will depend on the level of expertise of the learner and as Ericsson and Charness (1994) indicate, differences in expertise provide the largest and most reliable differences in performance among individuals. For example, if an electrical circuit diagram is presented to learners who have not yet acquired schemas that deal with typical combinations of interacting electrical elements, it is likely to be unintelligible by itself. Learners at this level of expertise require the text to understand how basic elements interact in achieving the circuit's function. For these learners, both the diagram and the text are essential, and so they will only understand the material once they have mentally integrated both sources of information. Cognitive load theory suggests that learning will be facilitated by physically integrating the two sources of information thus reducing the need for mental integration. Fragments of text can be integrated into a diagram in close proximity to corresponding components of the diagram. Arrows directed from the text to the corresponding elements of the diagram could be used to make the search process easier for learners.

In contrast, for more expert learners who have sufficient knowledge of different types of circuits, the text might be redundant because of previously acquired schemas. They still require the diagram to provide them with information concerning this particular, novel circuit. They may prefer to ignore the text but may have difficulty doing so when the text is integrated into the diagram. It should be possible to demonstrate the redundancy effect using learners at this level because the best instructional format with the lowest cognitive load for these learners may be a diagram-alone format.

Three experiments tested these hypotheses. The first experiment used inexperienced learners and was expected to demonstrate the split-attention effect. The second and third experiments were designed to investigate the alterations in ideal instructional designs with the development of expertise.

2 Experiment 1

2.1 Method

The experiment was designed to compare three instructional formats (integrated-diagram-and-text, separate-diagram-and-text, and diagram-only), using participants who had no formal electrical training. The participants were 26 first-year trade apprentices and trainees without any specialised training in electrical circuits and wiring. All of them had just commenced their first-year trade course.

All participants were tested individually. There were two areas of instruction, one relating to electrical switching for a bell and light circuit and a second with information for a water pump circuit. For each area, the experiment consisted of the instruction and test phases. During the instruction phase, learners were asked to study an instructional material at their own pace. After each participant had finished studying the circuit, they were asked to estimate how easy or difficult a circuit was to understand on a seven point scale, ranging from 1 (extremely easy) to 7 (extremely difficult). The results were interpreted as a measure of the subjective mental load associated with learning the materials (see Paas and Van Merrienboer, 1993).

Each test consisted of three parts. Part 1 was a reproduction task which asked participants to diagrammatically reproduce the circuit. For each circuit, a mark was allocated for each correctly drawn element (e.g., start button) in its correct position. Part 2 of each test consisted of test questions relating to each circuit (the circuit diagram was available during this part of the test). The circuit questions concerned about the operation of the circuit (e.g., “Which switches are closed when the bell and light are operating?”), as well as troubleshooting tasks where participants were presented with a textual description of a hypothetical problem in the circuit (e.g., After releasing the start button the bell and light stop working) and were required to suggest a possible cause for the proposed problem. Part 3 of each test consisted of fault finding exercises. A faulty diagram of a circuit was presented to participants. They were required to identify each fault in the circuit and propose a solution for the fault. Responses were assessed by the number of correctly identified faults with appropriate solutions.

2.2 Results and Discussion

The results from Experiment 1 are illustrated in Figure 1. Analysis of variance indicated a marginal difference between groups in time to process the instructions, $F(2, 23) = 3.08$, MSe = 3111.0, $p = .065$ for the Bell & Light materials, and a significant effect, $F(2, 23) = 12.49$, MSe = 3276.0, for the Water Pump materials (the .05 level of significance is used throughout this paper). Newman-Keuls tests indicated the instruction time for the diagram-only group was significantly lower than the separate-diagram-and-text for the Bell & Light test and significantly lower than both the integrated-diagram-and-text and separate-diagram-and-text groups for the Water Pump test.

The results from the subjective ratings of mental load indicated significant differences between the groups for both sets of instructional materials: $F(2, 23) = 5.22$, MSe = .59, for the Bell & Light circuit, and $F(2, 23) = 3.54$, MSe = .65, for the Water Pump circuit. Newman-Keuls tests indicated that the integrated-diagram-and-text format was perceived to be significantly lower in mental load than the diagram-only format for both sets of instructions and significantly lower than the separate-diagram-and-text groups for the Bell & Light test.

There was no significant difference between groups for the reproduction tasks of both sets of materials. There was, however, significant differences between the groups for the circuit questions for both sets of instruction: $F(2, 23) = 8.16$, MSe = 2.32, for the Bell & Light materials, $F(2, 23) = 5.83$, MSe = 6.40, for the Water Pump materials. Newman-Keuls tests indicated that the integrated-diagram-and-text group significantly outperformed both the remaining groups for the Bell & Light test, and the diagram-only group for the Water Pump materials. Results also indicated that the separate-diagram-and-text group scored significantly higher then the diagram- only group for the water pump test questions.

There were significant differences between the groups on the fault-finding task: $F(2, 23) = 11.75$, MSe = .635, for the Bell & Light task, and $F(2, 23) = 10.64$, MSe = .98, for the Water Pump task. Newman-Keuls tests indicated that the integrated-diagram-and-text group identified significantly more faults and solutions than the diagram-only group for the Bell and Light fault finding task. There also was a significant difference favouring the separate-diagram-and-text group

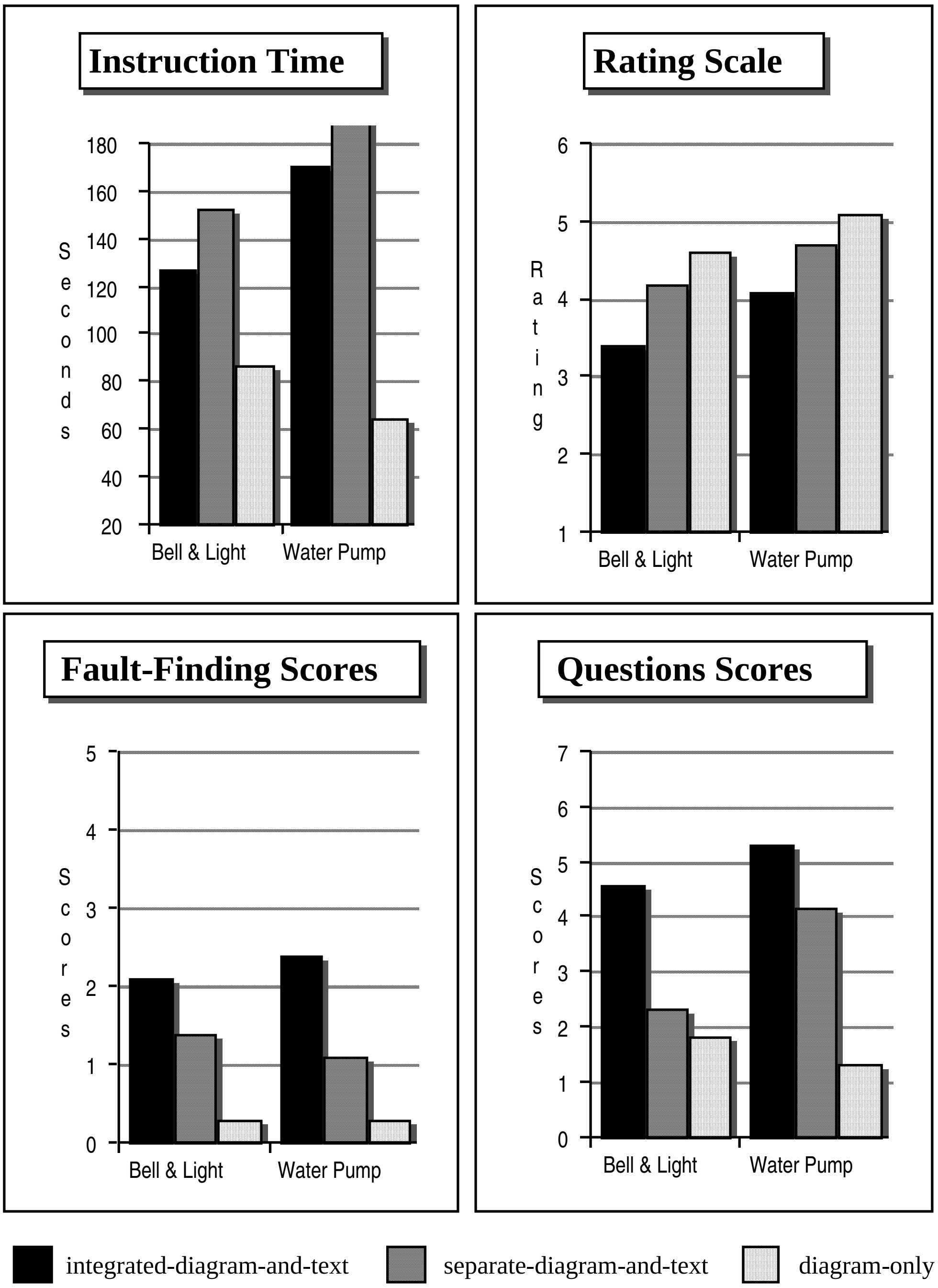

Figure 1. Charts of means for the data of Experiment 1.

over the diagram-only group for the Bell & Light test. For the Water Pump test, the integrated-diagram-and-text group was significantly better than both the remaining groups.

In Experiment 1, test performance indicated that the integrated instructional format resulted in superior learning and understanding of electrical circuitry compared to both a split-source format, demonstrating a split-attention effect, and a diagram-only format. The measures of subjective mental load supported the a priori predictions of the theory: the trainees in the integrated group reported the lowest estimates of mental load. The ratings of mental load were inversely related to performance, with high estimates of mental load accompanying poor test performance. Thus, the subjective ratings provide strong evidence for a cognitive load explanation of the results.

3 Experiment 2

3.1 Method

Experiment 2 was designed to first compare three different instructional formats using relatively inexperienced trainees, then provide these trainees with extensive direct training in electrical circuits, and finally to compare the same three instructional formats after the electrical instruction. Thirty-three first year apprentices from a Sydney company participated in the study. All participants had some limited knowledge of electrical principles and equipment after completing two months of their first year trade course. None of the participants had previous exposure to the instructional materials used in the study.

All the instructional and test materials for this study were computer based and constructed using Authorware Professional for Windows. The computer based training program was designed to display instructional materials as well as automatically record all experimental data including learners’ responses to test items, response times and subjective ratings of mental load. Every participant spent one session (about an hour) at a monitor (with breaks as needed).

The study was conducted in three stages. In Stage 1, trainees studied the electrical instructions of a motor with a starter and light indicators circuit in their respective experimental groups (up to 5 minutes were allocated to study). After studying these instructions, subjective measures of mental load were collected from all participants. A series of test items followed consisting of fault finding and multiple-choice questions.

Stage 2 was designed to provide one hour of direct training in electrical circuitry. Specifically, the materials consisted of in depth instruction in the operation and function of four slightly different electrical circuits. All circuits included the same basic structure of the starter used in Stage 1 and were designed to build domain specific schemas with starter based electrical circuits. A computer based integrated-diagram-and-text format was used for the presentation of instructions. As text explanations were introduced on the screen in physical proximity to the matching circuit entity both the text and relevant circuit element/s were highlighted, together with animation of changes to the circuit state. The instructions were entirely self-paced and provided a facility for participants to repeat each section. Participants also were allowed to take short breaks as they wished throughout the direct instruction period.

Stage 3 was identical to the Stage 1. Participants remained in the same groups as in the Stage 1. The entire study required learners to spend about 1 hour 45 minutes at the computer.

3.2 Results and Discussion

A series of three (instructional format) by two (pre and post training) ANOVA with repeated measures on the second factor were conducted. The variables under analysis were instruction time, subjective ratings of mental load, and test performance scores on fault finding and multiple-choice tasks.

Since the main purpose of this experiment was to study the dynamics of change in expertise, we were primarily interested in the interaction effect between groups and pre/post training. The interaction data of all the 3 × 2 ANOVA showed significant interactions for the fault-finding task, $F(2, 30) = 4.23$, MSe = .85, and for the multiple-choice items $F(2, 30) = 5.03$, MSe = .38. No significant interactions were obtained for the instruction time and subjective ratings of mental load. Interaction contrasts were carried out to isolate the source of significant interaction effect between the pre and post training. For the integrated-diagram-and-text and diagram-only groups results showed significant effects on the fault-finding task, $F(1, 30) = 4.76$, MSe = .85, and multiple-choice items, $F(1, 30) = 6.34$, MSe = .38. For the separate-diagram-and-text and diagram-only groups results showed significant effects on the fault-finding task, $F(1, 30) = 7.57$, MSe = .85, and multiple-choice items, $F(1, 30) = 8.45$, MSe = .38. For the integrated-diagram-and-text and separate-diagram-and-text groups all the contrasts were non-significant.

The significance of the interaction effects for a number of analysed variables suggests that the most efficient mode of instruction depends on the level of expertise of learners. As the level of expertise was raised in a specific instructional domain (i.e., basic starter based electrical circuits), the more effective format of instruction switched from integrated-diagram-and-text to the diagram-only format. In accordance with the prediction, as expertise increased, progress in performance of the diagram-only group was superior to both other groups.

4 Experiment 3

4.1 Method

The results of Experiment 2 indicated that participants still might not have reached a level of expertise where the textual explanations accompanying the diagrams become fully redundant. Experiment 3 was designed to use more intensive training in electrical circuitry to develop a level of expertise where text based commentaries become unnecessary. Experiment 3 was conducted about one month after Experiment 2. All the learners who participated in this experiment had participated previously in Experiment 2. In Experiment 3 they were divided into two rather than three groups: diagram-only and integrated-diagram-and-text groups. Fifteen participants were allocated to each of two groups. Those who previously had been in the integrated-diagram-and-text or diagram-only groups remained in the same groups. Participants from the separate-diagram-and-text group in Experiment 2 were randomly allocated to these two groups. By the time this study was conducted, all participants had received formal training in elementary electrical engineering as well as direct training in electrical circuits provided in Experiment 2.

As in Experiment 2, this study was entirely computer based. The experiment involved two stages. During Stage 1, all participants received additional direct training in electrical circuitry using materials which involved only starter based circuits. The training materials were in multimedia form, with text based explanations of circuits being replaced by auditory commentaries. The auditory information was coordinated with the circuit diagrams by providing screen based animations and highlights of the appropriate elements of the circuits. This training format has been shown to be an effective method of information delivery (see Mayer and Anderson, 1992). The training materials were self-paced and included a facility where sections could be repeated, as well as interactive exercises (multiple-choice questions, dragging elements of circuits to their proper locations, etc.) with hints and immediate feedback. This training period lasted for about one hour.

In Stage 2, participants were placed into their instructional format groups. They were asked to study instructional material with an electrical circuit slightly different from those studied during the training phase (Stage 1) but based on the same basic starter circuit structure. The instructional materials were presented in two formats for the two different groups, and learners studied them at their own pace but with a maximum of 5 min.

After the instructional phase, all learners were asked to rate the perceived mental load and then attempt a common test consisting of a fault-finding task and five multiple-choice questions relating to the operation and function of the circuit.

4.2 Results and Discussion

The results from Experiment 3 are illustrated in Figure 2. In order to take into account preexisting differences in learners' performance, analysis of covariance was applied to the data. The averaged scores of the Stage 3 in the Experiment 2 were used as a covariate in the analysis of covariance. Results revealed significant differences between instructional formats, $F(1, 27) = 4.83$, MSe = 1801.8 for the time to process the instructions; $F(1, 27) = 4.24$, MSe = 2.01 for the rating of subjective load; $F(1, 27) = 6.82$, MSe = 2.23, for the fault-finding test; and $F(1, 27) = 5.88$, MSe = .55 for the multiple-choice scores, with significant effects favouring the diagram-only group.

The findings of Experiment 3 provided considerable support for our hypothesis. When learners become experienced in a particular domain certain information that was previously essential for understanding becomes redundant and may impede further learning if processed. Collectively, the findings of Experiments 1 through 3 provide evidence that the "expertise" of the learner influences the efficiency of an instructional presentation with trainees benefiting from different formats at different levels of experience in a domain.

5 General Discussion

Together, the findings of this paper provide strong evidence that the efficiency of a design is in part due to the expertise of the user, with users gaining optimal benefits from different formats at different levels of expertise. Intelligibility of information presentation cannot be determined without reference to the learners for whom the information is intended. A module of information might be unintelligible to novices and thus require additional material with which it must be integrated. Physical integration should reduce cognitive load and enhance learning. The same module, presented to more experienced learners, may be both intelligible in isolation and also informative in that learners can acquire knowledge from it. Additional information is not needed because learners may have acquired schemas that easily and automatically allow inferences to be made. Those inferences cover the additional material that otherwise must be provided for less experienced learners to permit understanding. If such material is provided for more experienced learners, it is

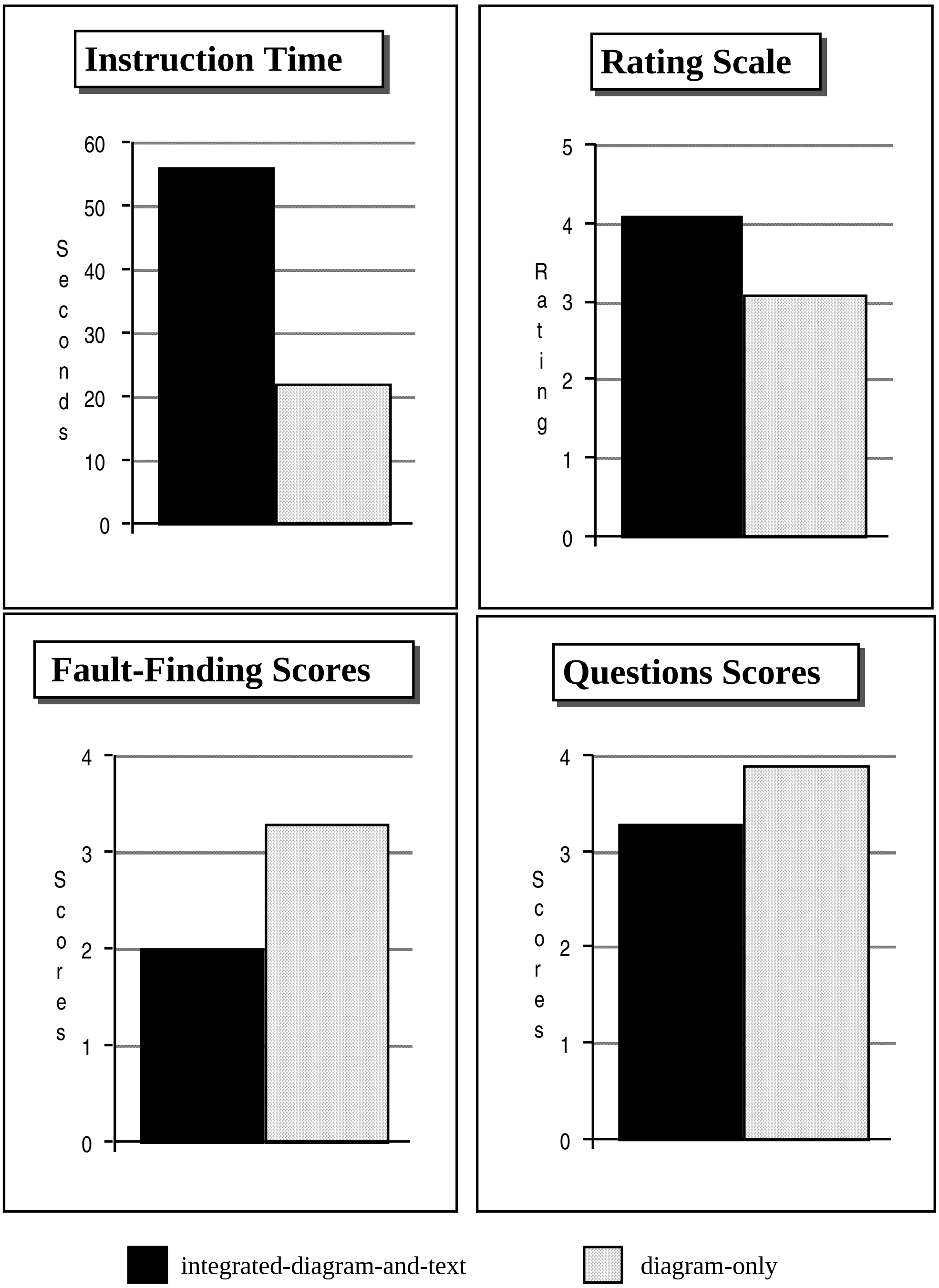

Figure 2. Charts of means for the data of Experiment 3.

redundant and processing it may unnecessarily increase cognitive load. These learners may be assisted by the elimination, rather than the integration, of the additional material.

The three experiments of this paper demonstrated the alterations in ideal instructional designs with the development of expertise. The cumulative nature of the results from the three experiments may be illustrated in Figure 3. The diagrams on the left side of the figure indicate that performance of the novices (Experiment 1) was very poor when presented with diagram-only instructions compared to integrated-diagram-and-text instructions. As can be seen from the subjective rating scale scores, these learners reported that the diagram-only instructions were more difficult to understand and learn from than the integrated-diagram-and-text instructions. As these learners became more experienced through the pre- and post-test of Experiment 2 and on to the substantial practice obtained by the same learners prior to Experiment 3, the relative effectiveness of the diagram-only and integrated-diagram-and-text conditions reversed with the diagram-only condition proving more effective and, based on subjective ratings, imposing a reduced cognitive load.

In the above experiments, the spatial grouping of text and diagrams was used as a method of information integration. It is reasonable to suggest that colour coding of corresponding elements of the separate text and diagram may produce a similar effect. Colouring elements of a diagram in the same colours as corresponding textual elements should reduce an unnecessary working memory load by reducing search processes involved with split source instructional formats. We tested this hypothesis in a preliminary study designed to compare two instructional formats (conventional separate-diagram-and-text and colour-coded-diagram-and-text) using participants without any substantial knowledge in elementary electrical engineering. The colour-coded-diagram-and-text format consisted of exactly the same diagram and text as the conventional format. The difference was that by clicking on any paragraph in the text, a learner could see all the electrical elements mentioned in this paragraph in the same unique colours in the diagram and text. The colour coded format group demonstrated a marginally lower subjective rating of learning difficulty and significantly higher test performance on question answering tasks than the conventional format group.

This preliminary study demonstrated that a colour coding technique can be used as an alternative to spatial grouping for the purpose of cognitive load reduction. With this technique, the same computer based colour-coded separate-diagram-and-text instructional format could be efficiently used for both expert and novice learners. Novices can use the colour coding to reduce search between referents while experts can ignore textual explanations that are unnecessary for them by selecting not to use the colour-coded feature of the presentation.

Thus, instructional presentations should be structured to reduce, as far as possible, the need for novice learners to search for and relate disparate sources of information. Spatially grouping or colour-coding elements of different sources of information that must be considered simultaneously is one way of reducing the cognitive load associated with search. On the other hand, if learners have considerable experience within a particular domain, an instructional format that eliminates, rather than integrates, redundant information may be a more efficient learning system. Unnecessary detail may distract these learners to a far greater extent than is sometimes thought. The importance of knowing ones users and specifying the level of expertise in an individual user model when designing user-adapted instructional presentations is clear.

In recent years, significant advances were made in building user-adapted instructional systems. But some instructional presentations might still be difficult to learn because they ignore some basic limitations of the human information processing system, especially the limited capacity of

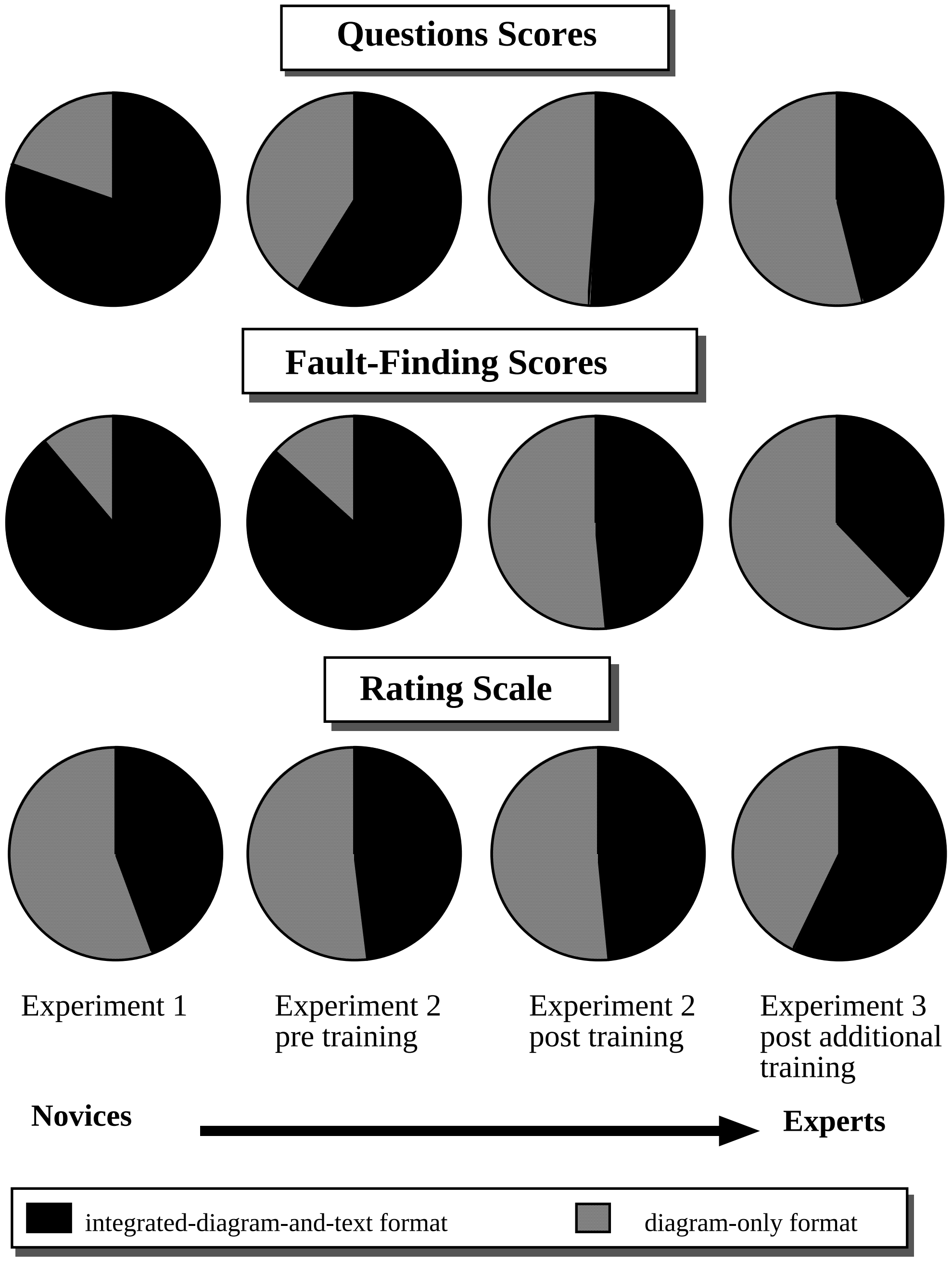

Figure 3. Relative performance indicators (comparative relations between corresponding means) on the integrated-diagram-and-text and diagram-only formats with increasing expertise.

working memory. The problem of user cognitive overload should be tackled when designing information presentations, and user expertise is an important factor to be considered by designers.

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