PROPOSED INSTRUCTIONAL DESIGN STRATEGIES FOR MATCHING OPERATOR LEARNING PREFERENCES WITH INSTRUCTIONAL FORMATS: A PRELIMINARY STUDY

Yi-hsiang Chang, University of North Dakota; Thomas R. Klippenstein, Andros Engineering

Abstract

Work instructions for manual assembly operations are basic to the activities of many industries. They are essential for completing a set of tasks in a correct sequence, making an assembly "complete." These instructions may be used to repair equipment, assemble components, or operate a machine. In today's manufacturing environment, one of the keys to success is rapid change to meet customer demands through mass customization. Workers must be flexible by learning a multitude of tasks, oftentimes through comprehending given work instructions, at a fast rate, including assembly of multiple types of parts during their shift or changing a machine's configuration to produce different parts. This paper reports a preliminary study to be used as a pilot or trial run on the test materials for a future, more comprehensive experiment. Other than just finding errors, missing information, or unanticipated consequences, a mixed method approach was utilized to investigate the interaction between the operator and given work instructions through both qualitative and quantitative data.

Introduction

To maintain their competitive advantage, manufacturers are moving toward a market where customization is key [1] and moving away from the mass production model. With this move, the need for rapid adaptability becomes crucial. Human labor is ideal for this rapid adaptability and, quite often, rapidly configurable automated processes can be impossible and/or not economically feasible. The close customer-manufacturer relationship in pre-manufacturing and post-sale activities, such as customer co-design process of products and services [2], increases the intricacy of business process planning. Along with product design and configuration [3], lifecycle activities for planning, manufacturing, and sustaining products and services need to be customized. Efficient data management is no longer the only key factor for successful mass customization; effective knowledge management throughout the product lifecycle [4] is now a key factor as well.

Manual assembly operation, an essential component in the mass customization environment, contains an inherent problem: "Expert" assemblers or technicians require a long learning curve and training, which can be expensive, particularly for processes that require problem-solving skills [5], [6]. It can also take months or years for a novice to develop the knowledge for high-complexity assembling processes. Moreover, even expert-level assemblers often must refer to instructions for infrequently performed or highly-complex procedures. In mass customization, field technicians and assemblers are challenged by frequently changing processes. To train assemblers each time assembly processes are changed is impractical and costly, especially with the fast pace of market competition [7]. One efficient way to solve this problem is having human manual assemblers cross-trained on different tasks to develop a deeper understanding of the whole process. Another solution is designing-for-assembly to reduce the skill level needed and cost of assembly. This concept has gained acceptance in mass production but it trades off flexibility and modularity, which may not be suitable for mass customization [8].

The quality of assembly operations relies on the experience of the assembler and the proper execution of the well-defined work instructions. The current practice for designing work instructions is not a collaborative effort between the job designer and the job executor and as a result no real-time feedback is available. General assumptions are often made about the needs of the job executor. Some research has been done to eliminate possible communication errors due to individual differences. Japanese researchers examined the use of language in the design of assembly instructions to accommodate a user's preference [9]. A study done by Matsumoto et al. [10] in Japan investigated the performance difference of novice workers using two different types of operating manuals of a facsimile machine: understanding-oriented and operation-oriented. The group of novice workers obtained a more favorable learning result using the understanding-oriented, or operator-centered, manual. Stanford University researchers contend that operator-centered instruction works better in practice through a study using the assembly instructions for a commercial television stand based on cognitive design principles [11]. The results indicated that cognitive design principles used in the assembly instructions reduce assembly time by an average of 35% and errors by 50%. Both studies of novice workers' behavior resulted in specific guidelines for creating effective help materials.

Incorporating individual differences into the design of assembly work instructions requires special attention to the learning and cognitive styles of the operator. Learning style refers to the learner's preference of instruction methods while cognitive style refers to the learner's approach to organize and retrieve knowledge [12]. Among numerous instructional theories, teaching according to the learner's learning style has shown effectiveness in practice for improving student learning [13]. There are four major learning style measurements that have effectively been used in education, namely the Myers-Briggs Type Indicator [14], Herrmann Brain Dominance Instrument [15], Kolb's Learning Style Model [16], and the Felder-Silverman Learning Style Model [13]. These instruments share the notion that teaching strategies can be used to improve learning outcome; however, classroom teaching of students is different from typical instructions received by industry workers. The most significant difference is the delivery means of instructional materials. In a classroom setting, the teacher may design and deliver the instructions based around the students' learning preferences, and may receive feedback before and after the activity from the students. For the trainers in industry, communication is typically one-way; special intervention covering individual differences cannot be available without the expert's presence. As a result, instructional design for the asynchronous learning environment is more challenging than that used in the classroom [17], [18].

One issue that has received relatively less attention in work instruction design is how the operator interacts with the instructional materials. When the job executors first receive instructions, they usually go through the "first run" phase as a mental mapping process [19]. First run refers to a situation where the operator is given a task similar to a previous task but not exactly the same. This situation can be found in mass customization production lines, product maintenance, and on-the-job training. Research on object assembly of mechanical systems [20] suggests that there are two phases of object assembly. When operators are exposed to a new assembly task, they first attempt to comprehend the basic assembly task to construct a mental model [21], and then execute the actual assembly process according to their mental model [22]. Operators continuously gather information from two major sources during the task comprehension process—work instructions or parts ready for assembly. The information of the given task may be delivered in different forms: either in visual, textual, or auditory forms presented by the work instructions, or in visual, auditory, or tactile forms presented by the objects. The construction of the initial mental model has mainly relied on visual information from both the work instructions and the objects, the textual description from the work instruction, and auditory if available. Tactile information may be used more often for mechanical assembly tasks as confirmation of visual and textual information [23], or for the verification and modification of the mental model through trial and error [24].

Studies done at the University of California, Santa Barbara, [25] concentrated on operator perceptions of work instructions. Those studies involved a human's understanding of a mechanical device and the role diagrams play in communicating this information. A cognitive model of how people read text and inspect an accompanying diagram was developed. This model indicated that people inspect diagrams for three reasons: to form a representation of information read in the text; to reactivate information that has already been represented; and/or to encode information that is absent from the text. Using data from participants' eye fixations while they read a text and inspected an accompanying diagram, Hegarty & Just [21] found that low spatial ability participants needed to inspect diagrams more often than the text. The data also suggested that knowledge of relevant information in a diagram might be a prerequisite for encoding new information from a diagram.

To summarize, as operators in mass customization production environments must continually learn new tasks, applying the principles of instructional design to address individual differences and, thus, enhance the instruction comprehension activity in manual assembly operations, will be beneficial. Previous studies have looked at the relationship between particular instruction and learning styles, operator experience, and cognitive ability. However, the objective of these studies focused mainly on collecting quantitative data, e.g. task performing speed and accuracy; how individuals interacted and responded to specific instructional types had not been thoroughly studied. This preliminary study employed a mixed method to better understand such phenomenon during manual assembly operations, with the intention of serving as a pilot study for a future, expanded experiment. The design of the testing materials and the experiment was described in detail. The finding of this study revealed rich information that had not been presented elsewhere and which not only helped identify issues of designed treatments, but also provided insight overlooked by other researchers. It was conducted to fine-tune the testing materials for future research by carefully examining operation-instruction interaction.

Development of Instructional Materials

To capture the essence of manual assembly tasks in industry, three of the most commonly used instructional formats were selected for this study: Step-by-Step, Exploded Diagram, and Demonstration Video. These formats were quite often used in conjunction with one another but, for this study, they were separated in order to observe the interaction between learning preferences and instructional formats.

The assembling of a battery-powered screwdriver, the 6V Tiger Driver, shown in Figure 1, was used as the context. There was an external lock for the bottom battery door; the trigger was to turn the screwdriver on and off; and, the switch on the top is to control the direction of rotation. This screwdriver, while inexpensive, possessed a certain level of complexity relevant to the common operations in an industry setting. The screwdriver was first disassembled, and eleven components were selected to design an assembly activity; the assembling of the harness, springs for battery contact, and screws holding the housings were not included as they required different work skills and instructions which were not the focus of this study. Through reverse engineering, a computer model of the 11-component screwdriver was built in SolidWorks to generate illustrations required by different instructional formats.

Figure 1. The battery powered screwdriver used in this study

A ten-step Step-by-Step set of instructions was first created based on the assembly process plan derived previously. Each step included text to describe the actions needed to complete the step along with corresponding illustrations showing how the part should be assembled. The Step-by-Step instructions, oftentimes in the form of training or maintenance manuals, is the most commonly used in industry and by the do-it-yourself enthusiasts for assembling and repairing products, as well as many other complex tasks. It seems to contain the greatest amount of information and is preferred by the visual learner who favors reading and studying the subject in a text and illustration format while performing a task.

An Exploded Diagram, commonly used in conjunction with Step-by-Step instructions, was created next. Shown in Figure 2, it did not have the number indicator and name for individual parts nor a Bill of Materials, which were provided in a separate instruction sheet for all participants. This instructional format shows part orientation and placement relative to other parts in the assembly; it does not indicate a particular order of assembly but implicitly indicates the parts closer to the center of the diagram are assembled first with subsequent parts being assembled in relative order of distance from the center. In the experiment, the Exploded Diagram was in the form of a single Letter size sheet of paper showing three views: exploded parts, assembled showing internal parts, and assembled showing the outside cases of the screwdriver.

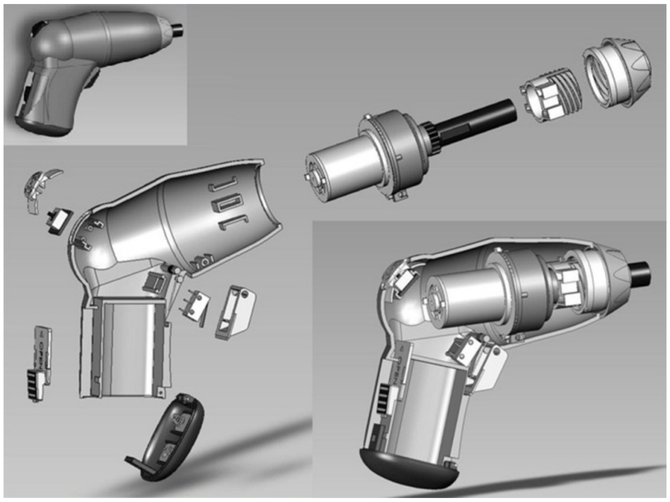


Figure 2. The Exploded Diagram used for the experiment

The Demonstration Video was developed from the Step-by-Step instructions using the animation function of SolidWorks, in the same assembly sequence to ensure that the same information was provided but in a different format. This instructional format is typical of on-the-job training and usually consists of an instructor demonstrating an assembly sequence to a learner. The learner, however, may or may not follow along with his or her own assembly what the video is demonstrating. Demonstration videos may be formal or informal, formal containing audio and onscreen notation, and may be slightly different each time it is performed. An animated set of instructions was used in this study as a surrogate for a live demonstration to make exactly the same information available to each participant. The video clip used did not have accompanying audio or onscreen notation.

There were a few alternatives, such as live physical demonstrations, a recorded video, or computer-based instruction, which could be used but were not chosen due to concern of treatment consistency, time, and facility constraints. For example, the trainer from a live physical demonstration might provide different participants additional or inconsistent information. A recorded video of a live demonstration, on the other hand, does not have the consistency issue; still, the time and cost to produce a good live demonstration video is fairly significant and was not suitable for this preliminary study. A digital form of the Step-by-Step instructions and Exploded Diagram in either PowerPoint or Adobe Acrobat File was also considered but not used because it changed the interface and interaction between the learner and instructional materials from the common printed media currently used.

Experiment

Ten undergraduate students from a four-year university on the West Coast of the United States were recruited from various Industrial Technology classes as participants. These students were of different major courses of study such as Technology, Engineering, and Business disciplines. Participants were invited knowing that they possessed certain skills and experience in manual assembly operations similar to that of those field assemblers in the "first run" situation. The experiment was conducted in a lab setting with the participants sitting at work benches during normal school hours. Noise and interruptions were minimal and lighting conditions were similar to typical industry settings. Basic information was given by the proctor for the purpose of the experiment and the progression of the experiment (Pre-test Survey, manual assembly activity, Post-test Survey). A verbal disclaimer stating their participation in this experiment was voluntary and in no way connected to their academic curricula was also delivered. The participants in return acknowledged with a verbal answer. The proctor also explained the need for their critique or feedback on the materials presented. No other information was given during the test. If a question arose about the assembly operations, the participant was asked to make a note and move on. This was done to ensure that all participants were given equal amounts of information and to expose errors in the materials.

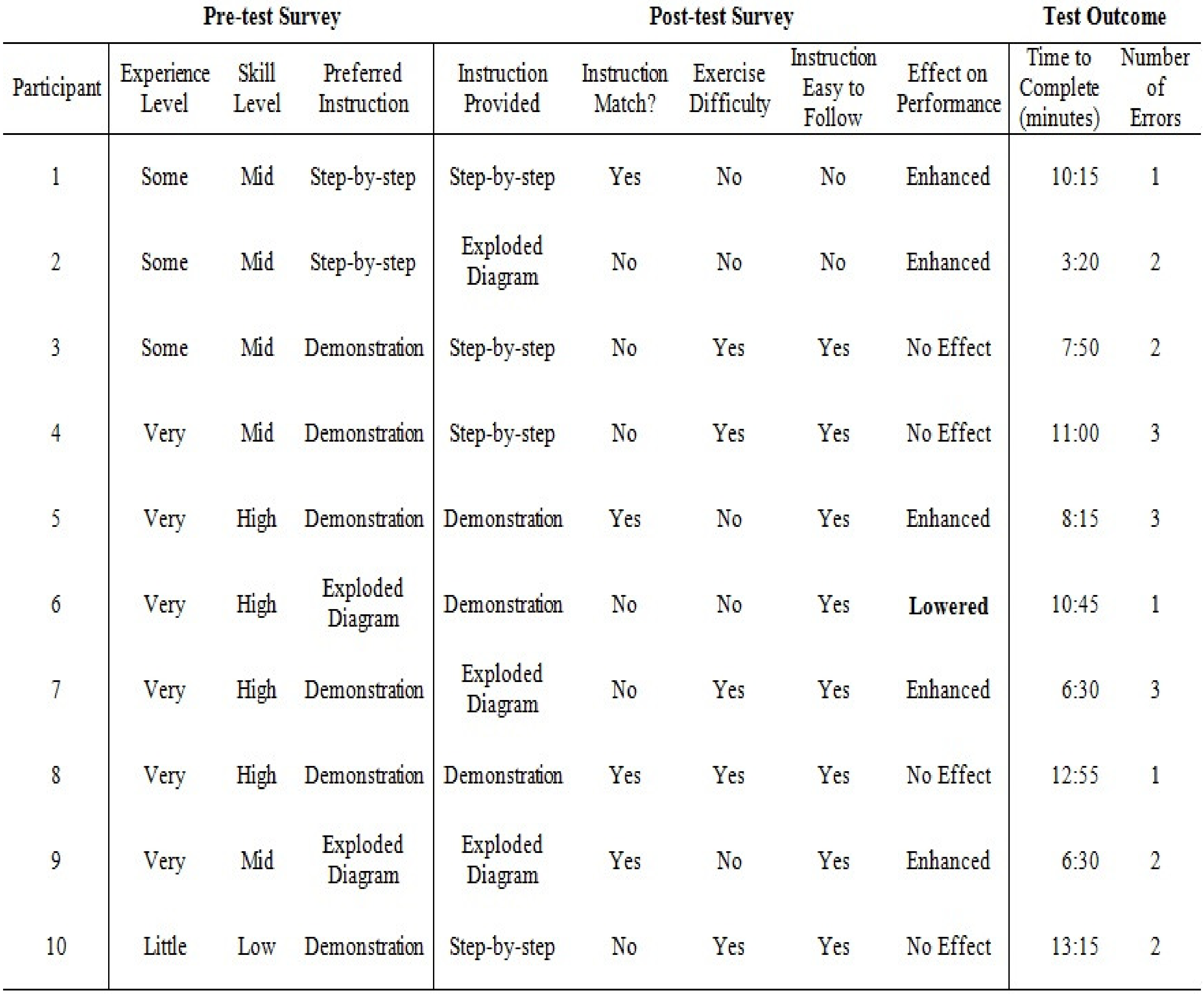
A multiple-choice, self-assessing pre-test survey was presented to the participants prior to their actual manual assembly tasks to collect information on their level of experience in manual assembly, self-assessment of their skill level in assembly, learning preferences (reading-writing, visual, and tactile) and preferred instructional format. The information gathered was then used to make a determination on the type of instructional material provided. Specific instructional material was then given to the participants along with a bag of eleven power screwdriver parts, as shown in Figure 2; no extra parts were provided.

The participants began the assembly activity and worked until completion. The participants were timed without notification while assembling the components in order to determine if their time to completion correlated with any other data collected. The timing started when the participant began following the instructional materials provided and stopped when the participants decided the assembly was complete. A multiple-choice, self-assessing post-test survey was then used to collect participants' feedback on the difficulty of the exercise, clarity of the instruction (to help identify missing information, unclear illustrations, improper sequences, etc.), and whether the specific instructions enhanced or had no effect on their task performance. The results of the post-test survey and overall impressions were then discussed for clarification of any issue and to ensure that all suggestions were documented. After the post-experiment discussion, the assembled electric screwdrivers were disassembled and inspected for completeness and errors in assembly. The surveys, task completion times, and assembly errors were then compiled to ensure that individual participant's data was kept together. For anonymity, and to elicit honest feedback, the participants' names were not recorded, nor was any system used to identify a specific individual's survey after it was submitted.

Pre- and Post-test Survey Results

Table 1 shows the results of the pre- and post-test surveys of individual participants as well as the time used to complete the task and number of errors they made. For the pre- and post-test surveys, individual answers were personal opinions and were not measured or verified by any test instrument. In the pre-test survey, six out of ten participants felt they were "very experienced" in assembling parts, while three reported that they had "some experience", and one participant claimed "little to no experience". The reported experience level, however, did seem to match the skill level indicated by the individuals, with four out of the six "very experienced" participants claiming that they had a "high skill level", while all of the "some experience" participants indicated having "mid skill level." The only "little to no experience" participant reported a corresponding "low skill level", who could be considered as a typical example of participants in some previous research.

Table 1. Data collected from Pre-test Survey, Post-test Survey, and Test Outcome



	Pre-test Survey			Post-test Survey					Test Outcome	
Participant	Experience Level	Skill Level	Preferred Instruction	Instruction Provided	Instruction Match?	Exercise Difficulty	Instruction Easy to Follow	Effect on Performance	Time to Complete (minutes)	Number of Errors
1	Some	Mid	Step-by-step	Step-by-step	Yes	No	No	Enhanced	10:15	1
2	Some	Mid	Step-by-step	Exploded Diagram	No	No	No	Enhanced	3:20	2
3	Some	Mid	Demonstration	Step-by-step	No	Yes	Yes	No Effect	7:50	2
4	Very	Mid	Demonstration	Step-by-step	No	Yes	Yes	No Effect	11:00	3
5	Very	High	Demonstration	Demonstration	Yes	No	Yes	Enhanced	8:15	3
6	Very	High	Exploded Diagram	Demonstration	No	No	Yes	**Lowered**	10:45	1
7	Very	High	Demonstration	Exploded Diagram	No	Yes	Yes	Enhanced	6:30	3
8	Very	High	Demonstration	Demonstration	Yes	Yes	Yes	No Effect	12:55	1
9	Very	Mid	Exploded Diagram	Exploded Diagram	Yes	No	Yes	Enhanced	6:30	2
10	Little	Low	Demonstration	Step-by-step	No	Yes	Yes	No Effect	13:15	2

Six participants preferred the Demonstration instruction method to learn about the subject, while Step-by-Step and Exploded View Diagrams were preferred an equal amount (two each). All of the participants classified themselves as tactile learners, needing physical hands-on experience to comprehend the assembly process. This dominant learning style may be due to the convenience sampling strategy of participants from technically related courses in college. In the planned future expanded experiment, a larger sample size with more diverse backgrounds should create a greater variation in all of the survey data, specifically the Learning Preference category.

As shown in Table 1, four of the participants received materials of an instructional format matching their preferred format, while six did not receive their preferred instructional type. The participants were evenly split when asked if the exercise was challenging. Eight of the participants reported the instruction provided was "easy to understand." One of the two participants who rated the instructions as not "easy to understand" was provided with a matched instructional format, while the other was not.

Five out of ten participants believed that the instructional material "enhanced" their manual assembly performance, while the other four reported "no effect," and one felt it actually "lowered" his or her performance. Comparing the Instruction Type Match to Effect on Task Performance revealed a relatively even spread of results. It should be noted that the preferred instruction type was self-reported by participants, who might or might not be aware of the distinction between different ones at the time of filling out the pre-test survey. By showing them examples of different instruction types at that point would have resulted in more accurate data. Similarly, individual Skill Level and Effect on Performance were based on the participants' subjective opinion. By providing a pre-test training activity, a more equal baseline among the participants in terms of task enhancement via work instructions could be achieved. In the meantime, individual skill level could also be assessed in a more objective manner.

Time to Complete

The Demonstration Video instruction used in the study lasted 6 minutes and 30 seconds; if the participants followed the video closely without shortcutting or fast forwarding, they would require a longer time to complete the task. The other two forms of instructional materials could be completed as quickly as the participants felt was needed. Shown in Table 1, the participants with Exploded Diagram instructions completed the task faster than participants with either the Step-by-Step or Demonstration Video instructions, whether or not the instructional type matched their learning preference. One explanation for this phenomenon was that an exploded diagram provided the least amount of explicit information for the participants to follow. It allowed the participants to assemble the components in the order they desired and did not make them read through text instructions or follow a demonstration.

Errors in Assembly

Errors in assembly tasks by individual participants were identified after the experiment. There were approximately twenty potential ways to assemble the components incorrectly. Inserting a part upside down or backwards would be an example of such errors. Table 2 shows the errors made by the participants, along with the individuals' time to complete the assigned task, instructional preference match, and claimed performance enhancement by the instruction provided. Out of the approximately twenty potential ways to make an error, only five types of assembly errors were observed:

- Type 1 Error: Motor/Shaft assembly and Front Knob/Threaded Collar assembly were installed outside of Left Side Housing.

Table 2. Summary of Participant Errors, Time to Complete, Preference Match, and Claimed Performance Enhancement by Instructional Materials Provided

Participant	Match	Enhanced	Time used (minutes)	Error Count	Error Type				
					1	2	3	4	5
1	Yes	Yes	10:15	1					X
2	No	Yes	3:20	2				X	X
3	No	No	7:50	2				X	X
4	No	No	11:00	3			X	X	X
5	Yes	Yes	8:15	3		X		X	X
6	No	Rev	10:45	1				X	
7	No	Yes	6:30	3	X			X	X
8	Yes	No	12:55	1				X	
9	Yes	Yes	6:30	2				X	X
10	No	No	13:15	2				X	X
Error Count Subtotal					1	1	1	9	8

- Type 2 Error: Direction Switch was upside down
- Type 3 Error: Front Knob was assembled into Left Side Housing incorrectly
- Type 4 Error: Front Knob and Threaded Collar were assembled incorrectly
- Type 5 Error: Trigger Spring position was incorrect

Errors made in the assembly might indicate missing or incorrect information, or too much information in that particular step in the instructional materials. Two types of error out of approximately twenty possible types during assembly accounted for over 80% of the assembly errors. The remaining three types of assembly errors occurred one time each, which might indicate an oversight on the part of the participant during assembly, but did warrant further investigation of the instructional material to determine if those assembly errors could be eliminated through revisions.

Feedback on Instructional Material

The participants were asked to provide feedback on all aspects of the experiment as well as the treatments. Overall, the comments were positive and many of the participants reported that the test was fun. The feedback reflected some of the assembly errors and a majority of the participants made the same comments. The most common issue was to add a definition of the components needed for each step at the beginning of the step. Other comments reflected the lack of accurate Trigger Spring position instructions and the spatial relationship of how the components fit together. Some of these comments were due to the inherent way a specific instructional form presented the information, such as how an Exploded Diagram would not show explicitly where or how the components fit together.

None of the participants using the Demonstration Video paused or rewound the video, indicating that the video clip progressed at a reasonable speed, or the participants did not feel the need to double check their work. Participants typically did not pick up the few components needed for specific step before beginning the instruction, so they tended to have to scramble in order to find components in the pile. All of the participants were surprised when their assembly was incorrect, and all believed that theirs was assembled correctly according to the instructions, although some areas were difficult to understand.

There were issues caused by specific instructional formats. The materials were functionally sound but contained a few easily correctable details in the procedure. The results of the participants' performance ratings in Table 2 indicated that two main errors were made during assembly regardless of the format of instruction provided, namely how the Front Knob was assembled to the Threaded Collar, and what was the proper position of the Trigger Spring. Due to its inherent lack of detail, the Exploded Diagram gave no indication of how those two steps could be accomplished; thus, it was typically used as a supplemental source in conjunction with the other instructional formats such as Step-by-Step.

The Exploded Diagram instruction used in this experiment consisted of a letter-size sheet with three illustrations. The main illustration displayed the parts exploded while the other two denoted the parts assembled without the Right Side Housing and assembled completely with no text instructions. To better serve its purpose, the Exploded Diagram should be expanded to three pages to provide a greater amount of information to the participants. The first page should consist of a Bill of Materials with illustrations for all of the individual parts and their respective nomenclature. The second page should display the parts in the exploded view with detailed callout illustrations for the Trigger Spring position and Front Knob to Threaded Collar assembly steps. Concise text notes should be added to each callout illustration to clarify assembly details. The third page should consist of two illustrations; one displaying the parts assembled into the Left Side Housing only and the other with all parts and both housings completely assembled. By implementing these changes, the Exploded Diagram could provide enough detail for the participants to correctly assemble the parts.

The Step-by-Step instructions used in this experiment were the basis for the other two instructional formats and contained some issues that might have affected individual assembly accuracy or caused confusion. The participants indicated that it was problematic to read the text, interpret the illustrations, compare the physical components, assemble the components in a single step, and then repeat the cycle. They tended to focus on only one aspect at a time and often skipped subsequent information presented in the same step of the instruction if they felt that portion had been completed. Such observations indicated that the amount of information and order of information in a given step was essential in fine-tuning the Step-by-Step instructions.

The Demonstration Video instruction was based on the Step-by-Step in illustrations and parts assembly progression; therefore, it contained the same errors as the Step-by-Step instructions. It should be revised to reflect the same part assembly order as the revised Step-by-Step instructions. The Demonstration Video instruction contained two technical issues that need correction. The video clip's resolution did not match a standard 4:3 monitor, so the participants were required to resize the video player window to fit individual video segments. Moreover, the video clips would only play on the QuickTime video player while they were supposed to be compatible with Windows Media Player. The school computers commonly available to students did not contain the proper plug-ins or add-ons, so all of the testing had to be done with a laptop not owned by the school; an experiment with more than one participant could be problematic.

Conclusions and Recommendations

A preliminary study utilizing a mixed method to investigate the interaction between the operator of a manual assembly activity and the given instructional materials was presented. The objective of this study was to explore the operator-instruction interaction through both quantitative and qualitative data, and serve as a pilot study for a future expanded quantitative study on whether a specific instructional format that matched the operator's learning preference would affect the speed and accuracy of manual assembly performance. Being a preliminary study, the intent of this paper was to report the qualitative data often neglected in previous studies and compare it with the quantitative data of the individual participant's task performance speed and accuracy.

The main limitation in this study came from the small sample size of ten participants, which was not large enough to have a high statistical power; thus, no correlation between variables or further statistical analyses were performed. The qualitative-centric results were only suitable for evaluating the instructional materials as well as the pre- and post-test surveys, and identifying possible reactions from the participants. Diversity of participants was another issue with this particular sample. For further research, a better screening process should be used to add variety or randomness to the participants recruited for the experiment, along with a significantly larger sample size. A power analysis prior to the experiment should be performed in order to determine the ideal number of participants.

One way to increase the diversity among participants would be to revise the pre-test survey and corresponding recruitment strategies. Besides soliciting participants' opinion of themselves regarding manual assembly related experience level, skill level, instruction preference, and learning style, more in-depth questions should be asked along with examples of different instruction types to determine actual preferences, making the data much more accurate and representative. For example, individuals might believe that they prefer the Step-by-Step instructional format, but a formal instrumental process would determine that these participants actually prefer the instruction in the Demonstration Video.

Running a similar experiment on a larger scale will require a large amount of data collection and analysis. By incorporating all of the materials into a digital format, potentially web-based, the data could be collected and analyzed quickly. The survey and the various instructional formats could be placed on a website connected to a database where the participants would follow on-screen instructions for all aspects of the experiment. The test results (errors in assembly) could then be logged by the proctor. However, it should be noted that the caveat to presenting all of the materials in digital format is whether or not it would change the perception as well as the task performance of the participants due to the interaction between the operator and the printed media, which might be different from that between the operator and the computer interface.

Some participants indicated difficulty in reading the text, interpreting the illustrations, comparing and assembling the physical parts, and then repeating the cycle. They tended to focus on only one area and skip over information that appeared previously accomplished when it had, in fact, not been. Further research into factors such as ratio of text or illustrations to actions per step, sequence of operations, order of illustrations, and any other aspects in the structure of the work instructions which may enhance the understanding of the instructions, will be another area for future investigation. The findings from any follow-up study will likely offer valuable suggestions for improving types and quality of instructional material used by technical trainers.

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Biographies

YI-HSIANG CHANG is an Assistant Professor of Technology at University of North Dakota. He received a B.S degree in Mechanical Engineering from Tatung University in Taiwan, a M.S. degree in Mechanical Engineering from Carnegie Mellon University, a M.S. degree in Industrial Engineering and a Ph.D. degree in Technology from Purdue University. Dr. Chang‘s research interests are in User-centered Product Design, Spatial and Cognitive Learning, and Product Lifecycle Management. Dr. Chang may be reached at yihsiang.chang@und.edu

THOMAS R. KLIPPENSTEIN is an R&D engineer at Andros Engineering in Paso Robles, California. He received a B.S. degree in Industrial Technology from California Polytechnic State University in San Luis Obispo. Prior to attending Cal Poly, Mr. Klippenstein worked for US Air Force over a decade, specialized in technical maintenance of aircraft.