Characterizing Diagrams Produced by Individuals and Dyads

Julie Heiser and Barbara Tversky

Department of Psychology, StanfordUniversity, Stanford, CA 94305-2130
`{jheiser, bt}@psych.stanford.edu`

Abstract. Diagrams are an effective means of conveying concrete, abstract or symbolic information about systems. Here, individuals or pairs of participants produced assembly instructions after assembling an object. When working individually, nearly all participants used a combination of text and diagrams. Those high in spatial ability produced the step-by-step action diagrams that in later studies were rated higher by all and improved performance of low ability participants. In a second experiment, pairs of participants assembled the object and produced instructions jointly. Pairs assembled the object faster and more accurately than individuals. Surprisingly, in the instructions produced, fewer than half the dyads used diagrams, and dyads produced fewer of the more effective diagrams. We speculate that the social verbal nature of the interactions of pairs encouraged verbal instructions.

1 Introduction

Designers, computer scientists, psychologists, and educators alike are interested in diagrammatic communication. Designing effective diagrams, whether for instructional, educational or computational purposes, is not simply a matter of realism. Effective diagrams abstract the essential information, and omit information that is irrelevant to the problem or task at hand. In addition, the spatial structures of diagrams provide a familiar foundation for spatial and conceptual inferences based on proximity, similarity, grouping, and more [e.g., 9, 14].

For conveying how to operate systems or how systems operate, diagrams are especially effective. Diagrams can convey structural information directly by depicting parts of a system in their spatial relations [20]. To convey dynamic or conceptual information, diagrams can be enriched with extra-pictorial devices such as arrows [7, 22]. Yet, diagrams are not always produced even in situations where they are most useful. For example, in a study of way-finding, most informants expressed a preference for using maps, yet most people writing down directional information provided words rather than sketch maps [24].

Benefiting from diagrams depends in part on the mental processes or resources the problem solver has to work with, whether expertise or ability [6, 10]. In particular, individuals low in prior knowledge or spatial ability often have more difficulty extracting relevant information and making inferences from diagrams [6, 7, 9].

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Specifically, it seems they have difficulties in “mentally animating” a system they are less familiar with, which could inhibit them from making correct inferences about the behavior of a system [6]. People are generally good at making perceptual inferences about the structure of a system, but spatial ability or prior knowledge are often needed to make inferences about motion, behavior, or causality from a static diagram. Often, in this case, verbal descriptions may be more helpful [8].

Diagrams are all too often poorly designed for all learners, high and low ability alike. A survey of thousands of visual instructions revealed many that were misleading, ambiguous, confusing, sometimes downright incomprehensible, causing frustration and error [8, see also 15]. An example appears in Figure 1. Our focus here is on assembly instructions, because they are so common, because they are often poorly designed, because they entail conveying both structural and functional information. As such, they are representative of a large class of diagrams meant to convey systems from how the heart works to how to pass a law. Assembling an object requires understanding both the structure of the system, that is, how the parts are to be configured, and the operation of the system, that is, the sequence of actions needed to put the parts together. Because assembly is both visual and spatial, diagrams are essential to effective instructions.

Clues to effective diagram design for all types of problem solvers can be obtained through user testing and empirical investigations. For example, Novick & Morse [13] found that in a complicated origami task, users needed step-by-step instructions. Participants in that study were unable to infer the intermediate steps from diagrams of the initial and final states. Maps provide another example. They have been refined by use of way-finders all over the planet for many generations. The natural process of iterative testing and refinement can be brought into the laboratory to serve as an empirical way to discover design principles. Informed participants are asked to produce instructions that will allow others to carry out the instructions or to understand the system [1, 8, 21]. Their productions can be rated and tested by users. Some evidence suggests that further benefits can be obtained by having participants work in pairs [e.g. 17]. Presumably, the iterative processes of producing and comprehending occur within the pairs, facilitating the refinement of instructions.

We are involved in a project to generate visualizations on demand, currently for assembly instructions. The aim is to create algorithms that instantiate empirically revealed cognitive design principles [see 1, 8]. In addition, because the process of assembly requires spatial transformations, often imaginal, we investigate the effects of spatial ability on production of diagrams and performance of an assembly task. Here we extend that project to collaborations of dyads in both object assembly and diagram production.

We report two projects on production of visual instructions by individuals and dyads. We chose a simple object assembly task, construction of a television stand, because it can be completed in a typical laboratory session and because it is representative of more complex tasks that rely on visual instructions and diagrams for instructional or learning purposes. To assure expertise in assembling the object, participants first assembled the TV stand using a photograph of the assembled TV stand as their only guide. Then they produced instructions. In the first experiment, participants worked individually; in the second experiment, they worked in pairs, or dyads. In addition we review the outcome of previous experiments where the quality of diagrams were rated and later tested by new participants so that the critical features of successful assembly diagrams could be extracted.

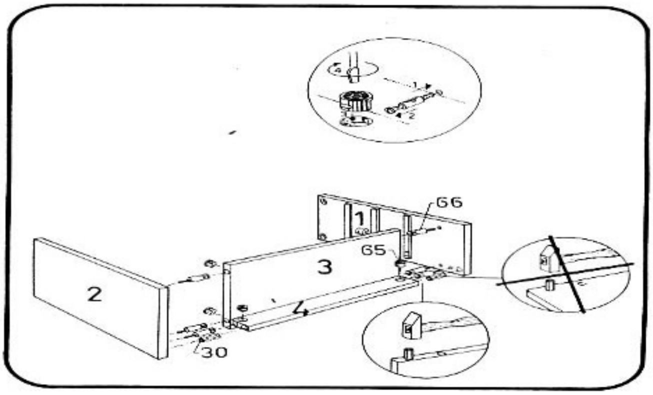


Fig. 1. This figure is a diagram illustrating how to assemble a drawer. This diagram contains several steps, incorporating several different parts and connector pieces, and also insets with more detailed instructions. In addition, there is no indication of order. According to Heiser et al., (2003), this would not be an effective representation for novice assemblers

2 Method

Participants completed the same task in Experiment 1 & 2. In Experiment 1, individuals completed it, whereas in Experiment 2, dyads completed the task.

2.1 Assembly and Writing Task

The object we chose to be assembled in Experiments 1 and 2 is a basic television stand, a standard build- your-own piece of modular furniture (see Figure 2). To participate in the experiment, participants could not have previously assembled this model or similar models of furniture. Assembling the TV stand is relatively simple: it consists of 5 major pieces (excluding wheels) and 2 types of connector parts, screws and pegs.

Participants were given a picture of what the assembled TV Stand looks like, and were given no other instructions as to how to assemble it. Figure 3 is a step-by-step schematic of the assembly process. In its most abstract form, the process consists of 5 steps.

Upon completing the assembly, participants were asked to create instructions to assemble the TV stand. They were told to use information they thought was necessary so that a novice assembler could efficiently and effectively assemble the TV stand, using diagrams and or text to convey this information.

Fig. 2. Picture of assembled TV Stand used in Experiments 1 & 2. The picture on the box, shown on the left, is the only picture participants in Experiment 1 & 2 had to assemble the TV stand

2.2 Individual Difference Measures

In both Experiment 1 and 2, participants completed a questionnaire about their prior experience with assembling or building objects, such as model airplanes, Legos, dollhouses, or other toys.

Participants also completed 2 tests of spatial ability, the Vandenburg and Kuse [23] test of mental rotation and the Money Spatial Navigation Task [12], a 1-minute test that evaluates egocentric perspective transformations. In the rest of the paper, we will be referring only to results from the Mental Rotation task [23] in terms of spatial ability. This test is a stronger predictor of performance (relevant to Experiments 1 & 2) than the Money Spatial Navigation Task.

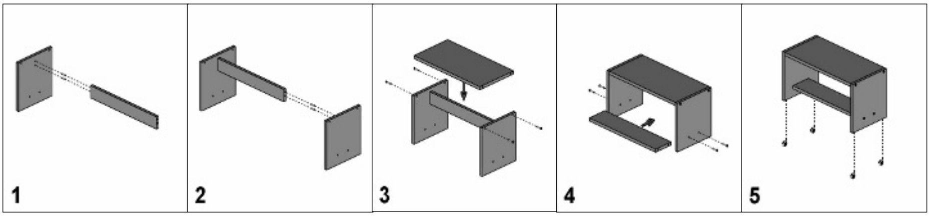


Fig. 3. Schematic depiction of steps to assemble the TV Stand (see Agrawala, et al, 2003, for origin of these instructions)

3 Experiment 1: Individuals Assembling and Creating Instructions

3.1 Participants

Forty-five Stanford University undergraduates participated for pay in individual sessions. The data of two participants were eliminated as they had participated more than once. Gender of participants was roughly equal in the final sample.

3.2 Procedure

Participants were tested individually. Each session began with a short interview assessing participants' prior experience with the TV stand, assuring that experience would not influence their performance. As described in more detail in Section 2, participants then assembled the TV Stand without instructions, only a picture of what the assembled TV stand looks like. Upon successful assembly, participants wrote instructions for assembling the TV stand.

4 Results: Experiment 1

Participants' scores on the spatial ability task were coded and participants were divided into high and low spatial categories using a median split, yielding 21 low and 22 high spatial participants. Participants had to perform below average to be included in the low spatial category, and above average to be categorized as high spatial. Both performance on the assembly task, and an analysis of the instructions produced (focusing on the diagrams) will be presented in the following sections. Performance and instructions were both highly correlated with spatial ability of the participant, and strong patterns were found in high and low categories, thus the results will be presented with respect of spatial ability scores.

4.1 Assembly Performance

All participants were able to assemble the TV stand without instructions. On the average, participants took 10.1 minutes (SD = 3.9) to assemble the TV Stand. Low spatial participants took 12.7 minutes (SD = 3.56 min) to assemble the TV stand, while high spatial participants completed the assembly on an average of 7.3 minutes (SD = 2.09 min), $F(1,41) = 36$, $p < .01$. Low spatial participants also made more errors during assembly, which manifested in the instructions produced (reported in the following section). Participants in Experiment 1 were not videotaped during assembly, so records of errors during assembly were not analyzed.

4.2 Analysis of Instructions

Even though participants had just completed the assembly task, nearly half of participants included an error in their assembly instructions. 86% of low spatial participants included an error of an "impossible action," such as putting the support board in (Step 2) after the top board was connected to both sideboards (Step 3) (see Figure 3). 12% of instructions produced by high spatial participants had such errors, $t(1,41) = 5.9$, $p < .01$.

The average number of assembly steps in the instructions produced by participants was 5.44 (SD =1.64) steps, which corresponds well with the steps portrayed in Figure 2. 42/43 (98%) of participants in Experiment 1 included some type of visual representation or diagram in the instructions they created. 26/42 (62%) of the diagrams represented information that was redundant with the text, and of these, all the diagrams were integrated into the text as tools for reference.

The diagrams used in these instructions (for both Experiment 1 & 2) can be categorized into 3 types of representations. First, people drew diagrams of parts, demonstrating the way parts look, sometimes to help differentiate 2 parts, and often times just used as sort of a part "menu." Second, people drew "structural" diagrams. A structural diagram is defined as 2 or more parts in configured position (see Figure 4). Structural diagrams could be used to show a step that has just been completed, or perhaps a demonstration of what your object should look like at a given point. Third, people drew "action" diagrams. Action diagrams are diagrams that represent, for example, 2 parts moving together, demonstrating the action between 2 structures. Note that action diagrams also contain structural information. Sentential representations of an action diagram, for example, would be "Put A into B, using a peg," or "Place A on top of B" (see Figure 4).

Differences between high and low spatial participants appeared in the sketches drawn in the instructions (see Figure 5 for examples of representative instructions). High spatial participants produced 2.67 action drawings per instruction set on average. By contrast, low spatial participants produced less than 1 (.64) action drawings per instruction set, $F(1,41) = 16$, $p <.01$. Conversely, low spatial participants included an average of 1.45 drawings that depicted the structure of the system, but high spatial participants produced only .81 structural drawings per instruction, though this difference was not significant due to high variance. Action diagrams necessarily depict structure, so the majority of drawings produced by the high spatial participants depicted both action and structure. Low spatial participants were more likely to include sketches of parts on their own (low had mean of 4.14 compared to high mean of 2.19, $F(1,41) = 5$, $p < .05$). In addition, high spatial participants were more likely to include diagrams with multiple perspectives, with information about depth and shading. Importantly, high spatial participants also made effective use of diagrammatic elements, such as guidelines and arrows to indicate placement or direction.

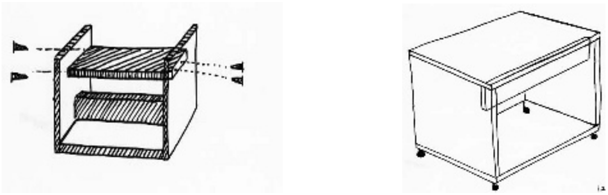
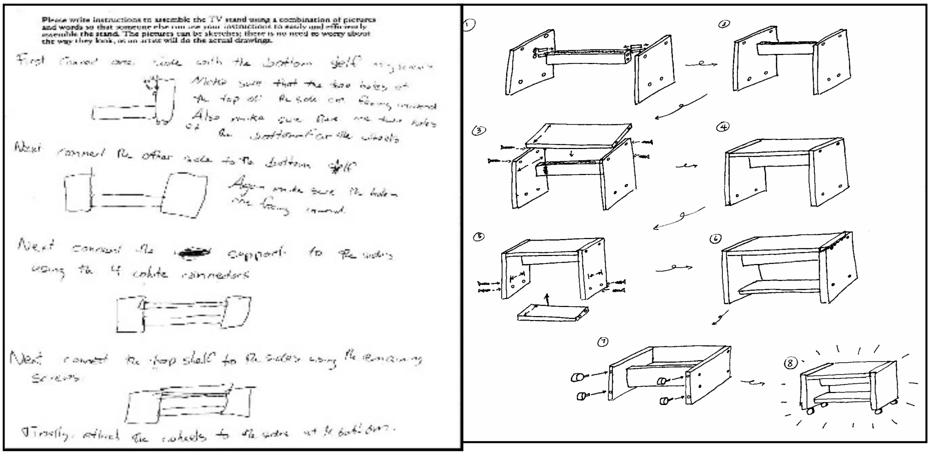


Fig. 4. Diagrams produced by participants in Experiment 1. The diagram on the left, with the shading, is an example of an action diagram, as it shows screws connecting 2 boards together. The diagram on the right is an example of a structural diagram, as it shows parts in configuration

5 Experiment 1: Conclusions

Diagrams are an integral part of instructions for an object oriented, visual and spatial tasks such as assembly. Participants, both more and less experienced, agree that diagrams are important as shown by the high number of participants that include



Please write instructions to assemble the TV stand using a combination of pictures and words so that someone else can use your instructions to easily and efficiently assemble the stand. The pictures can be sketches; there is no need to worry about the way they look, as an artist will do the actual drawings.

First connect one side with the bottom shelf using screws

Make sure that the two holes at the top of the side are facing inward

Also make sure that the two holes of the bottom are for the wheels

Next connect the other side to the bottom shelf

Again make sure the holes are facing inward.

Next connect the [illegible] support to the sides using the 4 white connectors

Next connect the top shelf to the sides using the remaining screws.

Finally, attach the wheels to the sides at the bottom.

Fig. 5. The figure of the left is an example of instructions from low spatial participant. The figure on the right is an example of instructions from high spatial participant.

them in the instructions (98% of participants). An analysis of the types of diagrams that users produce can aid in revealing design principles for effective instructional visualizations.

In follow up studies (discussed in more detail in [1,8]) we had participants rate the instruction sets produced by participants in Experiment 1 and extracted the factors of those instructions that influenced high ratings. These factors included but were not limited to step-by-step illustrations of the assembly process (see Figure 3 for an example of instructions produced algorithmically according to empirically determined cognitive design principles; from [1]), clear and explicit order of assembly operations, showing mode of attachment and relevant parts being attached, action diagrams instead of structural, and consistent and effective use of diagrammatic elements such as guidelines and arrows to convey actions. When these factors guide the design of assembly instructions, they improve performance of low spatial participants [8].

Besides educating the design of instructions, the results from Experiment 1 raise the important issue of individual differences in diagram comprehension and production. The differences in diagrams produced by high and low ability participants were striking. Participants low in spatial ability produced diagrams of part menus or structure, in contrast to the step-by-step action perspective diagrams produced by high ability participants. There are several possible interpretations, not mutually exclusive. Low ability participants may be uncertain how to depict action in static diagrams. Depicting action, perspective, and even structure may depend on mental rotation ability, on facility in holding complex figures in the mind and imagining them from other points of view. For low spatial individuals, language may be an easier way to conceptualize action [7].

The variation across individuals found in Experiment 1 motivated the design of Experiment 2, having dyads assemble the TV stand and create instructions. Would dyads create more effective visualizations than individuals, as Schwartz [17] found? Would collaboration compensate for effects of ability? Collaboration requires reconciliation of different points of view, which has the potential to yield better visualizations. Collaboration may also reduce error, as participants' errors may be independent, and they may catch each other's errors.

6 Experiment 2: Dyads Assembling and Creating Instructions

The method of Experiment 2 was identical to Experiment 1, except the assembly task and the instructions were done with pairs of new participants.

6.1 Participants

Participants were 34 students in an Introductory Psychology course at Stanford University participating to fulfill a course requirement. Each participant signed up with a person they did not know personally. This created 17 dyads. Overall, there were 22 men, and 12 women: 1 Female-Female dyad, 7 Male-Male dyads, and 9 Male-Female dyads.

6.2 Procedure

Participants were tested in pairs. Each session began with a short interview assessing participants' prior experience with the TV stand, assuring that experience would not influence their performance. Participants were told to work together to assemble the TV Stand without instructions, only a picture of what the assembled TV stand looks like. Upon successful assembly, participants worked together to write one set of instructions for assembling the TV stand. Generally, one of the participants did the writing while the other talked through it, but a few dyads switched off the writing task.

7 Results: Experiment 2

Participants' scores on the spatial ability task were coded and participants were divided into high and low spatial categories using a median split, yielding 15 low and 19 high spatial participants. Participants had to perform below average to be included in the low spatial category, and above average to be categorized as high spatial. Performance on these tasks allowed us to categorize the dyads in terms of spatial ability, giving us 5 Low-Low dyads, 5 High-Low dyads and 7 High-High dyads. There were no gender difference in performance and hence, none are reported.

7.1 Assembly Performance

Participants took an average of 6.6 min (SD = 1.8) Assembly times across spatial ability groups did not differ significantly. Only 2/18 (11%) of participants made an error in assembly (explained in section 4.1) that was reflected in the instructions they produced. Of the 2 dyads that made an error, one was a Low-Low dyad, and one was a High-High dyad.

7.2 Analysis of Instructions

The average number of steps to assemble the TV stand dyads included in their instructions was 6.4 (SD = 2.7). 9/17 dyads (53%) included one or more of the 3 types of diagrams in their instructions, parts, structural or action diagrams (see 4.2 for explanation). Thus, almost half of the instructions written by dyads only included text descriptions. 5/9 of the instructions with diagrams included action diagrams, either step by step or exploded diagrams. The remaining 4/9 included structural diagrams, and 2/9 participants included part menu, neither of which were from low spatial dyads. There were no significant differences in the instructions written across spatial ability groups.

8 Comparing Individuals and Dyads

8.1 Assembly Performance

Dyads assembled the TV stand more efficiently (M = 6.6 min) than individuals (M = 10.1), This is not surprising given that assembling is much smoother and faster when one person can stabilize the whole as another attaches parts. Because participants had only one screwdriver, parallel work was limited. For dyads, one participant could plan the next step while the other was performing an assembly step.

8.2 Analysis of Instructions

Only two of the 17 dyads made an error in their instructions. This contrasts with the instructions produced by individuals, where 20 out of 43 made an error in instructions. Fully 86% of the low spatial participants made errors in instructions in the first study. For accuracy, two heads were indeed better than one, especially for low spatial participants.

The dyads' improvement in instruction accuracy and in assembly performance was not mirrored in the quality of the instructions dyads produced compared to individuals. There was a sharp decrease in number of diagrams participants included in their assembly instructions. Ninety-eight percent(42/43) of individuals writing instructions in Experiment 1 included a diagram in their instructions whereas only 53% (9/17) of dyads did. Moreover, of the 9 dyads who included diagrams, only 5 included 1 or more action diagrams. Of the remaining 4, half included only a "menu" of parts, and half included a structural diagram. Only one person out of 43 individuals in Experiment 1 used only text in their assembly instructions, whereas, 8/17 dyads in Experiment 2 used only text. The omission of diagrams is significant because in other studies using the same task, users rated instructions with diagrams higher than instructions with text, and low ability assemblers benefited from instructions with clear diagrams [8].

9 Discussion

Design of effective instructions and explanations can be informed by testing the creations of experienced users. A classic example is maps, which have been used by cultures all over the world for many purposes.

Route maps, for example, have become highly refined to convey a route as a sequence of lines and nodes, with minimal embellishment. The refinement occurs as people produce and use maps with varying degrees of ease and success. The refinement of visualizations, then, occurs in a community of users, and the processes parallel those of establishing common ground in language [3]. The iterative design processes can be brought into the laboratory in order to uncover principles of effective instructional design.

A critical feature of many instructions and explanations, as for maps, is visualization. Diagrams use elements and relations on paper to convey elements and relations of instructions and explanations. Users can then understand diagrams by interpreting elements and spatial relations in the diagrams as elements and spatial relations in a broader spatial or abstract space. Effective diagrams convey only the essential elements and relations, removing irrelevant clutter. Because instructions and explanations are communicative, creating them in a communicative setting, by dyads instead of individuals, is expected to improve design of instructions and explanations. Schwartz [17] found that junior high school students working in pairs produced more effective diagrams in several scientific domains. Dyads' diagrams were more abstract and contained less idiosyncratic, often decorative rather than useful, information. However, even when diagrams are acknowledged as effective, they are not always produced [24].

Here, we compared individuals and pairs in an instruction design task. Participants first assembled a TV stand using the photograph on the package as a guide. Participants high in spatial ability assembled the TV stand faster and with fewer errors than those of low ability. After assembling the TV stand, participants produced instructions they thought would be sufficient for a novice assembler to complete the task. Nearly all the instructions created by individuals contained both diagrams and text. The effectiveness of the diagrams varied considerably, from simple menus of flat parts to a sequence of step-by-step perspective drawings that showed the actions required for assembly and used extra-pictorial devices such as arrows and guidelines to convey assembly. The more sophisticated drawings in the instructions were produced by participants that were high in spatial ability. In other research, the instructions produced by individuals were evaluated by new participants [8]. The step-by-step perspective drawings showing assembly actions were rated higher by participants of all ability levels. The lowest ratings were given to instructions where text dominated and diagrams were minimal. In a third study, low spatial ability participants benefited from more effective instructions, assembling the TV stand faster and with fewer errors [8]. Successful explanations, therefore, rely on diagrams more than text, and rely on sequential perspective diagrams that convey function or action as well as structure. For participants of high ability, the quality of instructions made no difference; in fact, they were hardly used, as the photograph on the package was sufficient.

Participants working in pairs assembled the TV stand with fewer errors than participants working individually. Although there were pairs where both individuals were of high or low ability as well as mixed pairs, spatial ability had no effect on assembly. The improved performance of even low ability pairs suggests that working together on this type of task can compensate for ability. Similarly, for dyads, spatial ability had no effect on quality of diagrams. Nevertheless, the improvement in assembly performance did not translate into creating more effective instructions. The surprising result is that only half the dyads included diagrams in their instructions, sometimes only a single diagram. What's more, dyads included fewer of the more effective kinds of instructions, those kind that showed action as well as structure. These results only seem to contradict those of Schwartz [17]; his participants were instructed to construct diagrams, and ours were free to invent the format of the instructions.

Why should dyads produce fewer and less effective diagrams than individuals? There are several ways to approach explaining this surprising finding, and more than one factor may be at work. One key reason may be that the dyads communicated between themselves by language. The natural extension is then to continue the task in language. This is a form of entrainment, a familiar process in establishing common ground, where cooperative collaborators take up each other’s formulations, language, and gesture [e.g., 4]. In addition, in the present situation, the dyads did not test the instructions they had written on themselves or on others, so they had no feedback on the efficacy of their productions. It is natural to think of the design processes of individuals as a conversation between the designer and whatever the designer places on paper [e. g., 16, 5, 19]. The designer may put diagrams on paper instead of language for several reasons. The design task is about something visualizable, and it is natural to translate something visualizable to a depiction. Then, thinking about something visualizable in order to refine it is easier from a diagram than from language, which needs to be visualized, an extra step. In addition, for the most part, dyads talk as equals; when they construct instructions, this symmetry is broken, as one partner typically dictates, and the other records. Turning diagrams into talk takes great effort, something dyads may avoid by extending talk into instructions. This analysis is consonant with the "Principle of Least Collaborative Effort" [2] according to which individuals sacrifice their "individual cognition" to facilitate the collaborative effort. We speculate that in the dyadic situation, the conversation does not take place over the pieces of paper that will constitute the instructions. Instead the conversation takes place in language, and prior to putting something down on paper. So the design is more likely to be in language, put down after the design conversation as a final product. For individuals, the design thinking, conversation if you will, takes place over the markings on paper, in this case, diagrams, which are a more direct mapping of assembly than language.

What is clear from the differences between individuals and dyads is that the effects are due to the dynamics of collaboration. The reasonable assumption is that participants have the same cognitive representations and procedures whether working alone or in pairs. If these were the only factors, then the outcomes of the dyads would be similar to those of individuals, perhaps comparable to the best performer in the dyad. An alternative account, one compatible with the discrepant performance of individuals and dyads, is that group cognition is distinct from individual cognition and the outcome is not equivalent to the average, sum, or best of the members' cognition. The social component of group cognition influences the dynamics between the individuals collaborating, which in turn influences the outcome of the collaboration. Further analyses of on-line creation of instructions should reveal the ways individuals and dyads interact with their own creations in design.

Acknowledgments

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