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AN EXAMINATION OF A CONCEPTUAL FRAMEWORK FOR PROCESSING AND INTEGRATING INFORMATION

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Flight crews rely on displays to assess the state of individual aircraft systems and to remain cognizant of how those systems interact. Degani, et al. (2009) suggest that understanding how humans routinely interpret complex environments should aid in creating displays that help flight crews gain holistic understandings of their vehicles. They propose a six-level hierarchy representing how humans integrate large amounts information. The current experiment sought to understand the costs and benefits of solving classic logic problems when details are presented at key levels of this hierarchy. The results showed that displays representing the highest level of the hierarchy yielded the highest accuracy across a diversity of task types. This effect was strongest when participants only allotted a small amount of time for understanding the problem and display before reading any questions.

Through real-world interactions, humans are faced with a wealth of information that they are able to process and use to solve problems and make decisions (e.g., Barlow, 2001). For example, when we enter a crowded room, we encounter details ranging from the color of the floor tiles to the disposition of the people with whom we interact. Despite the bustling confusion, we are still quite successful at integrating relevant stimuli to reach our goals. Such adaptations are less reliable when it comes to interacting with information on flight displays. One example is the case of Air Transat Flight 236, an Airbus A330-200 that had to make an emergency landing as the result of an undetected fuel leak (Government of Portugal, 2004; reviewed in Degani, Jorgensen, Iverson, Shafto, & Olson, 2009). Indicators notified crewmembers that the airplane was experiencing low oil temperature, high oil pressure, and low oil quantity. Through the relationship between the oil and the fuel systems, these indicators ultimately pointed toward a crack in the fuel line. This relationship was not apparent to the flight crew until quite some time after the landing. While in our day-to-day experiences, we are able to make sense of an abundance of cues, this task is particularly challenging when interacting with information presented in flight vehicles.

Controlling flight vehicles differs from everyday encounters in that flight crews are not fully immersed in the mechanics of their aircraft. Instead, they interact with displays intended to show information that is relevant for completing flight tasks. Degani, Shafto, & Olson (2006) and Degani, et al. (2009) propose that in order to maximize a flight crew's ability to interpret and make inferences about their vehicles, display designs should lend themselves to the cognitive processing we use in day-to-day encounters. Such an adjustment should make it easier for people to intuitively detect patterns and relationships as they do in natural settings. To do so, it is important to understand how it is that people are able to make sense of complex real-world environments. Degani and his colleagues propose a framework that outlines this process. The experiment in this paper examines this framework and its design implications.

The Hierarchy

Degani, Shafto, & Olson (2006) and Degani, et al. (2009) propose a hierarchical processing framework that represents how humans make sense of their surroundings. There are six levels of the hierarchy: *physical quantities, signals, data, information, structures of information*, and *order and wholeness*. Physical quantities are fundamental forms of stimuli in the environment, such as light waves, that may or may not reach our sensory organs. We can extract interpretable *signals* by activating designated neurons in response to certain light wavelengths or line orientations. We then transform these interpretable signals into meaningful *data*. Data includes any stimuli that are available for interpretation. Data is typically abundant and not filtered for relevance.

The remaining three levels are most important in the context of display design because they represent what is likely to be depicted on a display. After signals are transformed into data, we then abstract *information* from the data. Information differs from data in that it is “(1) relevant for the task and (2) meaningful and well suited to the users who need to perform the task” (Degani, et al., 2009; p. 5). Once we have isolated the relevant pieces of information, we integrate that information into *structures of information.* Beyond understanding what is important in a scene, structures of information allows us to also understand how the individual pieces of information are related to one another. Finally, the structures of information are organized into *order and wholeness.* The order and wholeness level represents having a holistic understanding of an environment and high-level patterns become apparent. It is at the order and wholeness level that people are best at making broad inferences and solving complex problems.

Testing the Hierarchy

According to the hierarchy, the optimal display for complex situations should present content at the level of order and wholeness (OW). This arrangement would give users the content and organization necessary to make inferences similar to the ones they make in natural settings. It is important to determine whether or not this is in fact the case. As shown in research examining how to best match displays with task demands (Bennet & Flach, 1992), one potential cost to presenting material at the level of OW could be decreased access to the structures of information (SI) level. Likewise, presenting material as SI could result in less access to information (I). The experiment described in this paper examines this potential cost by testing the hierarchy in its most basic form. As a precursor to directly applying the hierarchy to display design, we are interested in assessing the costs and benefits of applying the framework to solving standard logic problems.

Participants were given logic problem premises that briefly described the problem context. For example, one premise stated “Three of our Olympic swimmers (Mary, Tracy, and Nancy) posed for pictures in three different sports' magazines (Swimming, Splash, and Fast Lane). For their photographs each wore a different colored swimsuit (red, purple, and blue).” Each premise was supported by an external representation (ER) that corresponded with one of the top 3 levels of the hierarchy. Each ER would show, for example, that Tracy appeared on the cover of Splash. To represent the I level of the hierarchy, participants were given unintegrated lists of features that represented the variables needed for each question. ERs representing the SI level displayed unintegrated lists that were aligned in a way that lent themselves easily to integration. OW ERs presented groups of features in an integrated grid that outline the holistic relationship between features (see Figure 1).

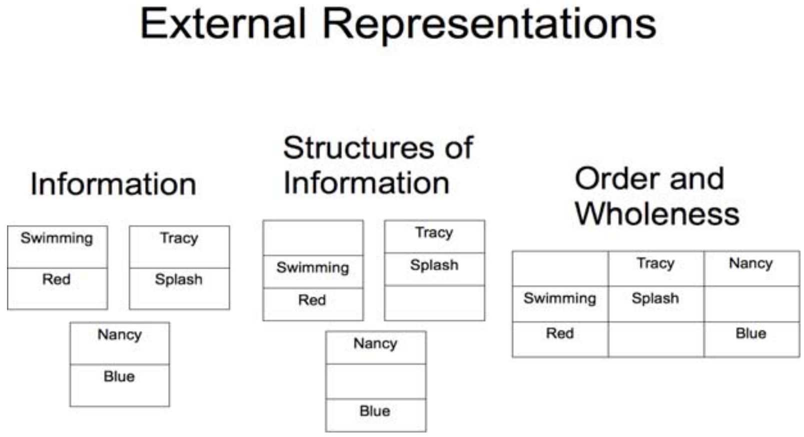
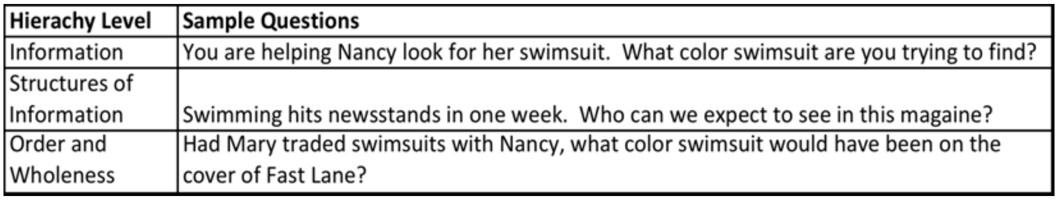


Figure 1: The types of external representations (ER) used to represent the top three levels of the hierarchy.

Following the ER presentations, participants were given questions that required them to interpret the situation at a level that also corresponded with one of the top three levels of the hierarchy. Questions about I required participants to draw from explicit information provided in the problem. Questions about SI could only be solved if participants integrated features in order to deduced one piece of implicit information. The final question type, representing OW, required participants to integrate group features in order to deduce two pieces of implicit information. An example of each question type is presented in Figure 2.



Hierachy Level	Sample Questions
Information	You are helping Nancy look for her swimsuit. What color swimsuit are you trying to find?
Structures of Information	Swimming hits newsstands in one week. Who can we expect to see in this magaine?
Order and Wholeness	Had Mary traded swimsuits with Nancy, what color swimsuit would have been on the cover of Fast Lane?

Figure 2: Sample questions used to represent each level of the hierarchy.

Drawing on the proximity compatibility principle (e.g., Wickens & Carswell, 1995), which states that performance should be optimized when displays parallel task demands, participants should have the most difficulty solving problems when ERs and questions do not align in the hierarchy. If, OW is the optimal presentation level, that ER should work best for all question types.

Methods

Participants

There were 32 participants in this study. Twenty-eight participants were summer psychology students at San Jose State University, and four participants were interns in the Human Systems Integration Division at NASA Ames Research Center, in California. One participant was omitted because he reported misunderstanding the instructions for the task. One participant was excluded because her accuracy level was at floor for all of the questions for one problem scenario. Of the 30 remaining participants, 12 were male and 18 were female. Their ages ranged from 19-years-old to 30-years-old, with a mean age of 22-years-old.

Materials

All stimuli were presented on a computer monitor using Super Lab software. Six experimental logic problem premises were created. Each premise description was made up of two sentences and provided context for the group of features outlined in each ER. Of the six experimental logic problem premises, half contained three groups of three features and half contained four groups of four features. Under the assumption that the 4X4 problems would be more difficult than the 3X3 problems, this variation was created as an exploratory measure of any effects of problem difficulty on performance. For each difficulty level, each premise was accompanied by an ER representing a different level of the hierarchy (see Figure 1).

Six questions were used for each problem premise. Two questions (see Figure 2 for examples) were designed to represent each of the top three levels of the hierarchy. To provide a response for each question, participants had to select one of four multiple-choice answers. The questions in each group ranged between 13 and 20 words (mean length = 16 words). Each multiple-choice response was one word long.

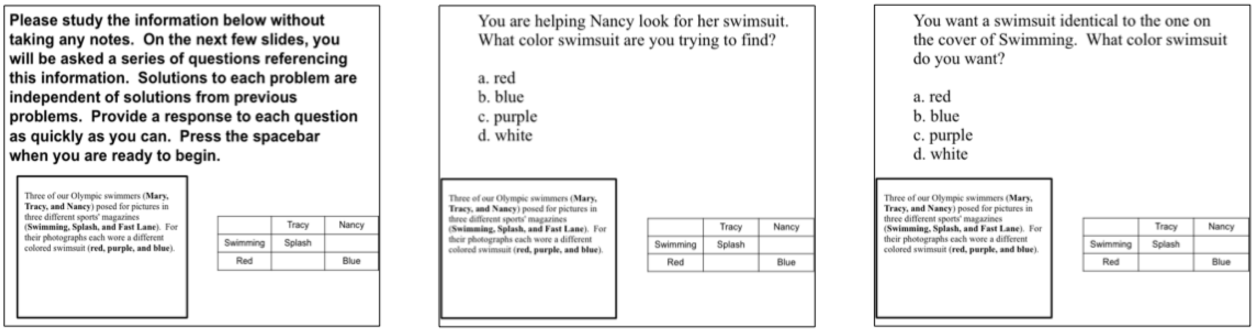
In addition, seven experimental filler questions were used. The filler questions were three and four-term series deductive reasoning problems adapted from Knauff and Johnson-Laird (2002), requiring a true-false response choice. The filler questions were created in order to break the monotony of the experimental logic problems and to divert attention from the experiment goals. Finally, a brief survey was prepared asking participants to report their background information, such as age and gender.

Design and Procedure

Questions were randomized within each problem. Half of the participants were given the 3X3 problems first and half were give the 4X4 problems first. Within each of the problem difficulty blocks, each of the problems was paired with an ER that represented one of the top levels of the hierarchy. Participants saw each ER type twice: once with a

3X3 problem and once with a 4X4 problem. The order of the ER types was randomized between participants. For consistency, the order for the 3X3 ER types always matched the order for the 4X4 ER types.

Once familiarized with the nature of the task, participants pressed the spacebar to advance to the first problem. They read the task instructions and reviewed the problem and corresponding ER. When they were ready, they pressed the spacebar and were presented with the first question. The problem and ER remained on the screen throughout the presentation of all of the questions. Figure 3 shows an example of an instructions and problem scenario screen, followed by two questions. Every set of six questions (one logic problem scenario) was followed by a filler question. The same structure repeated for each of the six problem scenarios. The amount of time spent on each screen (including the time to read each problem and study each ER) and proportion of accurate responses were recorded.



Please study the information below without taking any notes. On the next few slides, you will be asked a series of questions referencing this information. Solutions to each problem are independent of solutions from previous problems. Provide a response to each question as quickly as you can. Press the spacebar when you are ready to begin.

Three of our Olympic swimmers (**Mary, Tracy, and Nancy**) posed for pictures in three different sports' magazines (**Swimming, Splash, and Fast Lane**). For their photographs each wore a different colored swimsuit (**red, purple, and blue**).

	Tracy	Nancy
Swimming	Splash	
Red		Blue

Instructions and Problem Scenario

You are helping Nancy look for her swimsuit. What color swimsuit are you trying to find?

a. red
b. blue
c. purple
d. white

Three of our Olympic swimmers (**Mary, Tracy, and Nancy**) posed for pictures in three different sports' magazines (**Swimming, Splash, and Fast Lane**). For their photographs each wore a different colored swimsuit (**red, purple, and blue**).

	Tracy	Nancy
Swimming	Splash	
Red		Blue

Question 1

You want a swimsuit identical to the one on the cover of Swimming. What color swimsuit do you want?

a. red
b. blue
c. purple
d. white

Three of our Olympic swimmers (**Mary, Tracy, and Nancy**) posed for pictures in three different sports' magazines (**Swimming, Splash, and Fast Lane**). For their photographs each wore a different colored swimsuit (**red, purple, and blue**).

	Tracy	Nancy
Swimming	Splash	
Red		Blue

Question 2

Figure 3: The first screen presents participants with task instructions and initial introduction to problem scenario and ER. They are then given each question accompanied by the problem scenario and ER.

Results

A 2(difficulty level: 3X3 vs. 4X4) X 3(ER type: I vs. SI vs. OW) X 3(question type: I vs. SI vs. OW) repeated measures ANCOVA was run to test for interactions in accuracy performance between type of question and type of external representation, as well as to observe any performance differences in problem difficulty level (3X3 versus 4X4 problems). There was a great deal of variability in the amount of time participants spent reading each problem and studying the corresponding ER before viewing any questions (range of mean reading time across problems for each participant = 3740.34 - 78480.67 milliseconds; mean = 26844.12 milliseconds; standard deviation = 15920 milliseconds). To account for any advantages in allotting more time to understanding the problem scenario, this ANCOVA controlled for the amount of time it took participants to initially read each problem before beginning to answer the questions (referred to as "reading time").

The ANCOVA revealed no significant effect of difficulty level (F (1, 28) = .565; p =.46), so responses for 3X3 and 4X4 problems were collapsed. There was no interaction of ER and question type for accuracy (F (3, 79) = .451; p = .71, Greenhouse-Geisser assumed). There was a main effect of ER type (F (2, 56) = 3.416; p < .05). Participants were more accurate overall using the OW ERs than using the I ERs and the SI ERs (see Figure 4). The ANCOVA also revealed an interaction between ER type and reading time (F (2, 56) = 3.424; p < .05). To examine this interaction and localize the main effect of ER on accuracy between those with fast and slow reading times, the same 2X3X3 repeated measures ANCOVA was run isolating participants who took more time than average (more than 26844.12 milliseconds) and less time than average (less than 26844.12 milliseconds) to read each problem and study the display before proceeding to the first question.

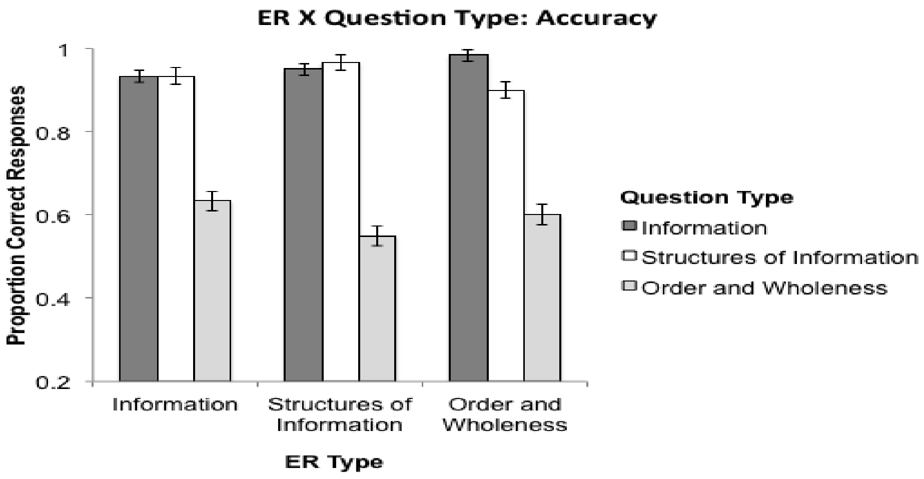


Figure 4: Accuracy responses showing an overall performance for ER and question types.

For participants who took more time than average to study the problem and the display (n = 12, minimum reading time = 26899.8 milliseconds, maximum reading time = 78480.64 milliseconds, mean reading time = 40112.1 milliseconds, standards deviation = 15730 milliseconds), there was no significant main effect of ER type F (2, 20) = .185; p =. 82). Eighteen participants took less time than average to read each problem scenario and examine each display (minimum reading time = 3740.34 milliseconds, maximum reading time = 26822.17 milliseconds, mean reading time = 17988.8 milliseconds, standard deviation = 8070.39 milliseconds). For this group of participants, there was a significant main effect of ER type (F (2, 32) = 7.884; p < .003). Participants were more accurate when answering questions using the OW ER. The interaction between reading time and ER type and accuracy is displayed in Figure 6.

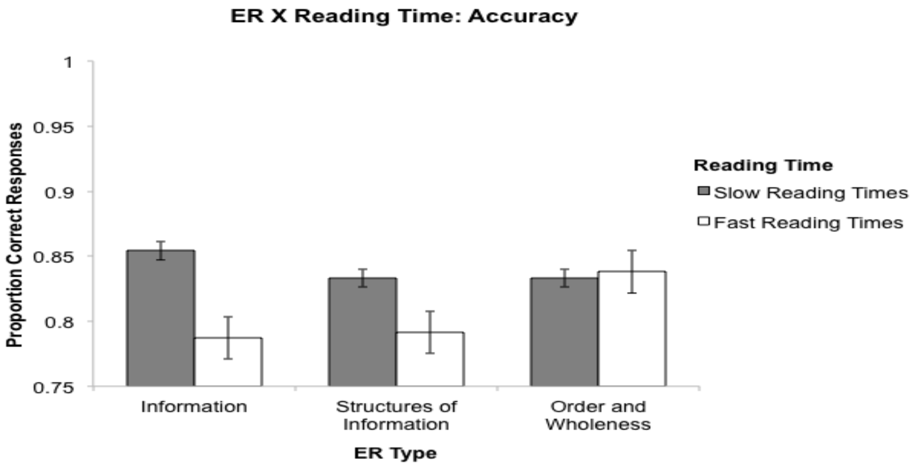


Figure 6: Accuracy responses between ER types for participants with slower than average and faster than average times reading times.

There was a main effect of question type (F (2, 56) = 31.778; p < .001). Participants were most accurate in answering I and SI questions and least accurate with answering OW questions.

Discussion

The current experiment was designed to test the hierarchical framework presented by Degani, Shafto, & Olson (2006) and Degani, et al. (2009) by examining the costs and benefits of presenting material at each level of the hierarchy. There was an overall advantage to using order and wholeness ERs across questions types. The OW advantage was driven by participants who spent less time than average examining each display and problem scenario before viewing any questions. This finding suggests that OW ERs are optimal in novel, fast-paced environments where committing time to fully understanding a scenario may not be possible. There was no interaction between ER and question type. Participants were significantly less accurate when answering questions representing OW (most likely because the OW questions were more complex), but this was true across all three ER types.

One limitation of this experiment was that only one approach to integration was used to represent the different levels of the hierarchy. Participants may have had an easier time using the OW ERs because matrices are commonly used to solve logic problems (e.g. Novick & Hurley, 2001). To account for this limitation, future studies should examine alternative ways of creating integrated ERs beyond traditional matrices. Independent of this limitation this experiment identifies an advantage of using integrated displays.

The Order and Wholeness level of the hierarchy respresents having a high-level understanding of the existing patterns in an environment. For the types of problems used in this experiement, the advantages of having a display represent high-level patterns was strongest when less time was spent examining ERs or understanding the problem premise. The findings from this experiement have positive implications for using OW displays to improve performance in time-constrained situations. When information about high-level relationships is available, problems can be solved more accurately without large time allottments for prior problem scenario and display understanding.

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