

# The Interaction between Informational and Computational Properties of External Representations on Problem-Solving and Learning

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## Abstract

This paper reports an experiment that explores if the way instructions for operating a complex device are represented influences problem-solving and learning about the task. Instructions were presented in one complex representation or in multiple simpler ones. The form this information took was tabular, diagrammatic or textual. Participants found the optimal solution more often when given instructions in text representations or in a single representation. However, the single text representation was associated with significantly slower performance. Participants recalled more about the task with text representations, irrespective of how the information was distributed. This experiment confirmed that representations that display instructions in such a way as to increase the cost of operating with them can paradoxically lead to better performance.

## Introduction

There are many claims for the benefits that multiple external representations (MERs) can bring to learning and problem-solving (*e.g.* Cheng, Lowe & Scaife, 2001; Kozma, Chin, Russell & Marx, 2000, Najjar, 1998). However empirical support for the benefits to learners is mixed with some studies reporting benefits of using MERs in educational environments (*e.g.* Cox & Brna, 1995; Mayer & Sims, 1994; Tabachneck, Koedinger & Nathan, 1994) and some not (*e.g.* Ainsworth, Bibby & Wood, 2002; Tabachneck-Schijf & Simon, 1998).

One key factor underlying the advantages that MERs can bring to problem-solving and learning is that of computational non-equivalence. Representations that theoretically contain the same information (informational equivalence) differ in the ease with which people can extract this information. Larkin & Simon (1987) contrasted interpretation of graphical and textual representations in terms of search, recognition and inference. They showed how search processes are considerably more efficient in diagrammatic rather than textual representations. They propose that textual representations have a high cost of perceptual enhancement when compared to the diagrammatic representations. Tables tend to make information explicit, emphasize empty cells that directs attention to unexplored alternatives, and allow quicker and more accurate read-off. (*e.g.* Cox & Brna, 1995; Meyer, Shinar & Leiser, 1997). These findings help explain the

match-mismatch hypothesis (Gilmore & Green, 1984) that argues that no notation is perfect; it is only good with respect to a particular task. For example, Bibby & Payne (1993) showed that providing participants with different representations that explained the operation of a complex device facilitated alternative aspects of the task. Identifying a faulty component was helped if instructions were presented as procedures whereas a topological diagram improved recognition of a misaligned switch. Consequently, MERs may offer benefits for solving complex problems by allowing for these alternative perspectives.

However, the majority of the research on MERs has addressed only the computational properties of representations without also considering how information is distributed. The combinations of representations that studied were almost invariably informationally redundant, *i.e.* informational equivalence was held constant to explore computational differences. Yet, a common reason to use MERs is to distribute information over a number of separate representations, so that each one displays a subset of the total information. This is often done when one representation would be very complicated if it expressed all the necessary information (Ainsworth, 1999). It is likely that there may be a match-mismatch effect for informational as well as computational properties of representations.

One possibility is that separate ERs that isolate dimensions of information will allow learners to focus on separate aspects of the tasks. Each aspect could be learnt separately and then integrated with others when it was fully understood. Ainsworth, Bibby & Wood (1997) found that two ERs that each displayed a single dimension of information allowed children to learn to perform an estimation task faster than two ERs that simultaneously displayed two dimensions of information. This was true when the information was represented in both mathematical expressions and pictures. In this case, it would appear that multiple simple ERs allowed learners to incrementally build their knowledge of the task, so facilitating performance.

However, a single ER that contains all the necessary information may facilitate problem-solving in other circumstances as it: a) minimizes the number of ERs to be learnt; b) can make explicit the relations between dimensions of information; and c) presents this information in close proximity, which has been shown to reduce a split-

attention effect (e.g. Chandler & Sweller, 1992). Cognitive load theory suggests that a single integrated ER (normally text and graphics) improves learning by reducing the working memory demands associated with integrating information (e.g. Kalyuga, Chandler & Sweller, 1999).

One further prediction that follows from the mismatch hypothesis is that ERs that enhance the efficiency of problem-solving may not be the same ones that facilitate learning. Svendsen (1991) showed that a command-line interface to the Tower of Hanoi task led problem-solvers to spend more time per trial, but they engaged in more planning and were able to remember more about the task. O'Hara & Payne, (1998) similarly found that increasing cost of operations in the 8-puzzle led to increased planning. ERs that increase the users' cognitive load may require learners to remember, evaluate, and design better solutions to problems.

This paper explores whether the informational and computational properties of ERs interact to influence problem-solving and learning. The ERs provided instructions for operating a complex device – an Alchemist's Factory. The task required chemicals to be bought, combined in specific ratios, placed in the appropriate apparatus (which must be paid for) and set to correct values. Furthermore, participants were asked to create gold in the cheapest possible way, so there are multiple solutions for this task that differ in their cost and complexity. Accordingly, the task requires information to be integrated (for planning solutions) but then efficient operation of the factory requires focusing on single factors. Instructions were presented either in one complete ER or in MERs, where each presents only a subset of the necessary information. They were displayed in text, diagrams or tables

### Hypotheses

- 1) *Does the form of an ER influence efficiency and effectiveness of problem-solving?* It is proposed that the diagrams should enhance search and recognition compared to text. Hence, participants given diagrams should solve the problem faster. The structuring information provided by tables should also make them more efficient than text.
- 2) *Does the complexity of an ER influence efficiency and effectiveness of problem-solving?* Finding the best solution should be facilitated if all the information is available in one ER, as different solutions can be compared directly. However, there may be no difference in efficiency. Planning should be faster with one ER, but performing the task should be facilitated by separating information as this will reduce cost of navigation and may enhance memorization.
- 3) *Does the form and complexity of an ER interact to influence efficiency and effectiveness of problem-solving?* We hypothesized that text, given its high cost of search and recognition, will take longer to study when presented as a single complex ER. However, diagrams and tables should be more efficient when presenting complete information as the additional costs of navigating more complex ERs will be minimized as diagrams and tables facilitate search and

recognition. However, if the research on adding interface costs to encourage planning also applies to these ERs, then it is possible that there will be reverse effects of the effectiveness of problem-solving: i.e. better solutions will be found when ERs are costly as hence single text will be the best ER.

4) *Does the form and complexity of ERs interact to influence learning?* Two alternative hypotheses are proposed. Learning is facilitated when working memory demands associated with search and recognition are lower as this promotes transfer to long term memory. This suggests that diagrams and tables will enhance learning (Cognitive Load account). Alternatively, learning is facilitated by ERs that are associated with high costs of search and recognition as participants will be encouraged to remember this information. Consequently, the complexity of the single text ER may lead to enhanced learning (Interface Costs account).

## Method

### Design

A two factor between groups design was used. The first factor (*complexity*) had two levels: *single*, which presented instructions in one complex ER and *multiple*, which presented the same instructions but in four simpler ERs. The second factor (*form*) had three levels: *table*, *diagram* and *text*.

### Participants

Eighty-four students took part in the experiment for payment (£4). There were 56 females and 28 males with an average age of 21.5 years.

### Materials

Participants were requested to create gold using an Alchemist's Factory in the cheapest possible way. A typical step in single text form is "Gold Ore is a liquid. Sulphuric Acid is a liquid and costs 30sl per litre. These can be mixed together in the mixer to form Gold. The Mixer costs 5sl per use. 1 unit of Gold is made from 1/2 a unit of Gold Ore and 1/2 a unit of Sulphuric Acid. The Mixer settings to make Gold from Sulphuric Acid and Gold Ore are 1 hour and fast" (see Figure 1 for the equivalent step in the complex diagram and <http://www.psychology.nottingham.ac.uk/research/credit/projects/alchemy> for all the ERs). There are six such steps that can be combined in various ways, as there are a number of possible recipes for making gold. The *single* versions of the task present this information in one ER. The *multiple* versions present this information in four separate ERs, which are not available co-presently. The content of the ERs are:

- *Chemicals* - the costs of buying available chemicals
- *Apparatus* – the costs of using a piece of apparatus
- *Formula* – the combinations of chemical required to create new chemicals
- *Settings* – the apparatus settings.

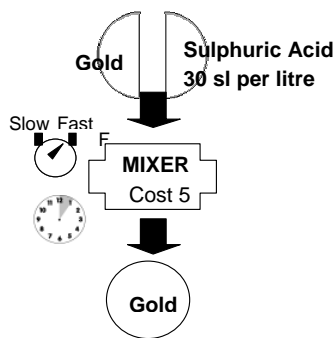


Figure 1: A single step in the integrated diagram

The design of the ERs was piloted to ensure that they were as clear as possible.

### Apparatus

The six different versions of the Alchemist's Factory were created in Macromedia Director. Instructions are available before starting the factory and on request once inside the factory, but are not visible when someone is interacting with the factory. In the single version of the task, one button can be pressed to request the instructions. In the multiple version, there are four buttons that access the separate ERs, labeled as above.

### Procedure

The Alchemist's Factory gives an introduction to the task and shows a step similar to one from the "gold" task. Participants were provided the appropriate form of instructions labeled with explanatory text. The experimenter demonstrated the use of the factory by following these instructions. Participants were told that their aim should be to make gold in the cheapest way. They then worked independently with the factory until they were successful. If participants made an error, they were informed at the end of that step, and could repeat the process. After making gold, participants were asked to teach their apprentice to operate the factory by recording as much of the process as possible. They were given pen and paper and told they could use any format for recording this information.

### Dependent Variables

No single D.V will provide a complete picture of the task so multiple DVS were calculated. Efficiency was assessed by the amount of time that participants spent studying instructions. This was also computed prior to participants making their first move as indication of initial time spent planning. The effectiveness of ERs was determined by calculating the number of errors made in operating the factory and the solution participants chose. Learning was assessed by examining how many items the participants recalled correctly during the teachback. Given that participants who choose more complex solutions have a greater opportunity to recall more items, this was also coded

as a percentage of the maximum they could have recalled given their solution.

## Results

To examine the influence of information and computational properties of the form of the instruction on problem-solving and learning, a [2 by 3] between groups MANOVA was computed (Table 1). Analysis revealed a single main effect of complexity ( $F_{1,78} = 130.11$ ,  $MSE = 151.79$ ,  $p < 0.001$ ); unsurprisingly the total of instruction requests was much higher when the instructions were presented in MERS. There were significant main effects of form on time spent studying instructions overall (Figure 2) and prior to making a first move ( $F_{2,78} = 5.17$ ,  $MSE = 29921$ ,  $p < 0.01$  &  $F_{2,78} = 6.71$ ,  $MSE = 8731$ ,  $p < 0.002$ ). Post hoc comparisons showed that text was associated with significantly greater times than either tables or diagrams overall ( $q = 3.6$   $p < 0.05$  &  $q = 4.1$   $p < 0.05$ ) and with tables prior to operation ( $q = 5.18$   $p < 0.01$ ).

These main effects were modified by significant interactions between form and complexity (overall,  $F_{2,78} = 4.01$ ,  $MSE = 29921$ ,  $p < 0.025$  & prior to operating factory  $F_{2,78} = 4.37$ ,  $MSE = 8731$ ,  $p < 0.02$ ). Simple main effects showed that complexity influenced text but no other form of ERs ( $F_{1,78} = 6.52$ ,  $MSE = 29921$ ,  $p < 0.02$  &  $F_{1,78} = 7.52$ ,  $MSE = 8731$ ,  $p < 0.01$ ) and that the form of ERs was only significant for single ERs ( $F_{2,78} = 9.0$ ,  $MSE = 29921$ ,  $p < 0.001$  &  $F_{2,78} = 9.0$ ,  $MSE = 8731$ ,  $p < 0.001$ ). Tukey's post-hoc comparisons showed that single text led to significantly greater instruction times than both single diagram or single table overall ( $q = 5.20$ ,  $p < 0.01$  &  $q = 5.19$ ,  $p < 0.01$ ) and for prior to operation ( $q = 4.48$ ,  $p < 0.01$  &  $q = 5.71$ ,  $p < 0.001$ ).

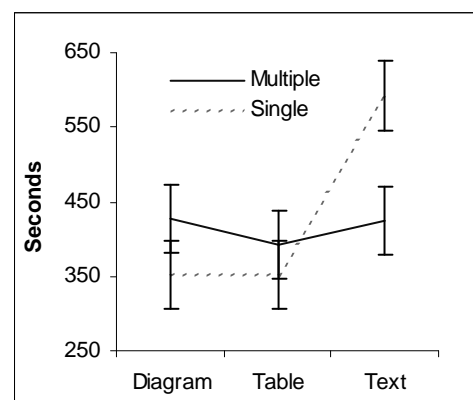


Figure 2: The time spent studying instructions overall by complexity and format (with std error bars)

The form of representation influenced what participants recalled about the task - total number of items recalled ( $F_{2,78} = 5.12$ ,  $MSE = 72.98$ ,  $p < 0.01$ ) where text was associated with significantly greater recall than tables ( $q = 4.47$   $p < 0.01$ ) and the percentage of items recalled ( $F_{2,78} = 4.32$ ,  $MSE = 4.46$ ,  $p < 0.02$ ) where tables was associated with significantly worse percentage recall than either text or diagrams ( $q = 3.79$   $p < 0.05$  &  $q = 3.34$ ,  $p < 0.05$ ).

Table 1: The influence of representational complexity and form on problem-solving and learning.

	Multiple			Single		
	Diagrams N = 14	Tables N = 14	Texts N = 14	Diagram N = 14	Table N = 14	Text N = 14
No. Requests	53.3	52.5	51.9	22.4	22.2	21.1
St. Dev.	(13.8)	(12.0)	(17.2)	(8.3)	(13.3)	(5.9)
In. Times	426.7	392.1	424.9	351.4	351.8	591.9
St. Dev.	(134.1)	(166.0)	(178.1)	(166.6)	(163.3)	(218.7)
In. Times (pre)	193.0	121.0	161.3	148.4	117.5	260.2
St. Dev.	(82.7)	(49.3)	(71.3)	(86.5)	(54.4)	(166.1)
No. Errors	1.7	2.0	1.4	2.1	1.1	0.9
St. Dev.	(1.8)	(2.1)	(1.8)	(3.0)	(1.1)	(0.9)
Items Recalled	20.6	19.2	27.6	27.3	18.6	24.5
St. Dev.	(10.6)	(8.8)	(4.4)	(8.9)	(8.1)	(8.9)
Percentage Recalled	48.9%	43.3%	59.9%	64.8%	43.4%	57.0%
St. Dev.	(19.2%)	(19.2%)	(13.8%)	(18.1%)	(21.9%)	(15.8%)

**Key:** In. Times = time studying instructions in seconds; In. Times (pre) = time studying instructions prior to making a first move. No. Errors = mistakes in operation; Items Recalled = items correctly recalled after the task; Percentage Recalled = percentage of items correctly recalled given the participant's solution.

Pearson correlation co-efficients were calculated to determine if time studying instructions was related to performance. Instruction time correlated with number of errors, but there was no correlation between instruction time and what participants recalled.

Table 2: Pearson correlation co-efficients

	2	3	4	5	6
1. No. Requests	0.26*	-0.03	0.34**	-0.09	-0.15
2. In. Times		0.67**	0.34**	0.02	-0.04
3. In. Times (pre)			0.01	0.09	0.09
4. No. Error				0.03	0.05
5. No. Recalled					0.85**
6. % Recalled					

Note: \* =  $p < 0.05$ , \*\* =  $p < 0.01$ , (two tailed test).

To determine if the nature of the ER influenced whether the best solution to the problem was found, the number of participants who identified this ideal solution (irrespective of whether they made any errors in following this solution) was calculated by complexity (Table 3 Panel A) and form (Table 3 Panel B).

Chi squares analysis showed that there were more optimum solutions in the single conditions ( $X^2 = 3.42$ ,  $df = 1$ ,  $p < 0.032$  (one sided as hypothesized)). There was also a trend for the form of ER to affect if the optimal solution was found ( $X^2 = 5.57$ ,  $df = 2$ ,  $p < 0.062$  (two sided – no hypothesis)).

Table 3: Optimum solutions by (a) complexity (b) form

	Optimum Solution	Other Solutions
Multiple	10	32
Single	18	24
Diagram	8	20
Table	6	22
Text	14	14

Finally, whether the form of instructions influenced the way these instructions were recalled was examined. Three ERs were evident in the records – text, diagrams (either as a flow chart or the presented diagram), and a formula ER that consisted of a pseudo chemical notation (Figure 3). One subject produced a table (in the diagrams condition). The form of instruction influenced the way that participants recalled information (Fisher's exact = 12.71,  $p < 0.05$ ). Three one way chi squares showed that that were equal number of formula representations in all three conditions but that use of text ( $X^2 = 7.47$ ,  $df = 2$ ,  $p < 0.03$ ) and diagrams ( $X^2 = 5.92$ ,  $df = 2$ ,  $p < 0.05$ ) was affected by condition.

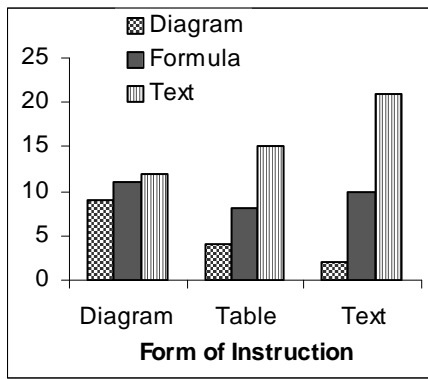


Figure 3: Form of records by instructional form

Irrespective of the number of ERs studied, participants tended to integrate all the information into a single ER (Fisher's exact = 2.40,  $p = ns$ ) (Table 4).

Table 4. No of ERs in records by complexity.

	One	Two	Three
Multiple	29	10	2
Single	33	7	0

## Discussion

We had predicted that participants given the text representation would take longer to complete the task than those given either concrete diagrams or tables, given the advantages their known advantages for search and recognition. This is what we observed. There was no main effect of complexity on instruction reading time. Overall MERs did not take significantly longer to read than single ERs even though there is an increased cost of interacting with them through the interface (it takes 120 ms for each ER to be displayed which adds an average of less than four seconds for reading times in the MERs conditions). However, the form and complexity of ERs interact to influence performance. The text disadvantage was only present with the single complex ER - representational form did not affect efficiency when multiple simpler ERs were used.

The number of participants who found the best solution for the problem was also influenced by the way that the instructions were represented. As predicted, a single complete ER did help participants to find the optimum solution. Presenting information in one ER seemed to allow easier comparison of information, which helps participants identify the best solution. There was also a trend for ER form to influence whether the best solution was found. Participants given text found the optimum solution more often. Overall, more people in the single text condition discovered the optimal solution than in any other condition (9/14 in ST compared to a maximum of 5/14 in the other conditions).

Given this pattern of results, the findings are more consistent with the interface costs accounts rather than the cognitive load account. Given the lower instruction reading times, participants appeared to find complex diagrams and tables easier to understand than complex text, even though diagrams were of novel form. This increased cost of operation seemed to encourage people to engage in more planning behavior. In this case increased planning was associated with increased performance.

After successfully completing the task, participants were asked to record as much of their solution as possible so as to teach their apprentice how to make gold. Consequently, it was possible to assess a simple form of learning – how much information participants had successfully encoded during the task. The form of instruction influenced the amount of information people recalled about the task. Participants in the table condition remembered less about the task than people in the text or diagrams conditions. The complexity of the ER did not influence recall – multiple and single ERs were associated with similar recall.

Two alternative hypotheses were identified for the influence of ERs on learning. One possibility was that those ERs that make the task easier by reducing working memory demands whilst problem-solving, would facilitate learning. The second hypothesis was that ERs, which are difficult to search, will lead to greater learning, as participants will aim to minimize the time spent searching by memorizing information. The results do not unequivocally support either hypothesis. Recall in both text conditions was nearly identical – yet the single text had been associated with increased instruction time and best solution, whereas the multiple text led to no more reading time than the other MERs. In fact there was no relationship between time spent studying instructions and what was subsequently remembered about the task.

One possibility is a stimulus-response compatibility between mode of presentation and record of learning. Although participants could use any form of ER, a high number chose to use text. Overall, nearly 60% of people use either text by itself or combined it with a pseudo-chemical ER. In the text condition, 88% of participants used a text form compared to the diagrams condition (50%) or table condition (62.5%). A third of the participants saw a table representation, but none chose to use that form of ER in their records. Tables require initial commitment to all dimensions of information in order to identify rows and columns. This is likely to be very difficult if you can remember less than half the task. We are examining if the nature of the learning task that interacts with the form of ER to produce these results by examining participants transferring to a second Alchemist's Factory task. If the table is simply harder to record, then recall should be lower on paper records but not lead to under performance on transfer tasks.

Overall, there is little evidence that problem solving or learning was enhanced by using MERs, adding further evidence for the negative effects of MERs. However, that the results depend upon an interaction between the

computational and information properties of the ERs reminds us to be cautious about generalizing from previous studies that only contrast MERs with different computational properties. Furthermore, this task requires participants to integrate information from separate ERs in order to successfully plan solutions. That they did so is evident from the fact that the majority of post-task records, the ERs are in a single integrated form. If tasks require less coordination of information then potentially MERs may be more beneficial. Furthermore, all the ERs in each condition were of the same form (i.e. all tables or all diagrams or all text). Once information is distributed, it can be represented in different forms. For example, it may be the case that information primarily useful for planning should be presented textually, whilst that aimed at efficient operation of the device could be given in tabular form.

### Conclusions

The results of this experiment suggest there is a complex relationship between computational and information properties of ERs and their effects on problem-solving and learning. The optimum form of ER depends on whether the task was to find the single best solution, to find a satisfactory solution in a time-effective manner or to memorize the most about how to complete the task.

These results suggest that if the aim is to encourage people to find the optimum solution to a problem, then performance will be facilitated if the instructions are presented either in text rather than diagrams or tables and/or in one complete ER rather than in MERs. As the most successful ER was single text, it would suggest that this may occur, apparently paradoxically, because of the difficulty of working with this form of ER. However, finding this solution occurred at the expense of increasing time spent reading instructions. Hence, if the goal is to encourage quick task completion or if solutions are roughly equivalent, then the worst ER to select may be a textual ER that presents a great deal of information. In this case either using MERs, or a single diagram or table will facilitate performance.

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