Do People Posses a Global and Ordinal Understanding of Accumulation ? An Experimental Study

Mihaela Tabacaru, System Dynamics Group, Universitet i Bergen, Helen Fischer and Nadia Said, Psychologisches Institut, Universität Heidelberg

People's seemingly poor ability to understand accumulation principles is well-documented. We argue for a distinction between information processing of the accumulation tasks, and how this information is retrieved. Understanding of the accumulation principle contains one necessary and sufficient condition: having a correct representation of the causal relations between the system parts, such an understanding being global and ordinal in nature. In an experimental study with college students, we test this hypothesis by systematically varying two dimensions of how one accumulation problem was presented: (a) type of visual search referring to whether people process the information given in an analytical (local) or holistic (global) manner; and (b) type of information retrieved, referring to whether the information people extract is categorical or ordinal in nature. As expected, we find that a problem format that induces global search enhances people's understanding of accumulation compared to a problem format that induces local search, whilst the ordinal dimension is less significant. Implications for the current debate in the failure to understand stock and flow are discussed.

People´s seemingly poor ability to understand accumulation principles is a well-documented issue. Several studies have shown that people have problems applying the basic accumulation principles correctly, like the relation between inflow, outflow and the level of a stock (Cronin et al, 2009). The poor performance in accumulation tasks, i.e., the poor ability to apply accumulation principles to tasks that ask about the relation between inflow, outflow and the level of a stock, has been explained in several ways , however having problems applying the principles of accumulation does not necessarily mean that people do not possess an understanding of them in the first place.

In investigating accumulation understanding, most researchers have used graphical tasks, in which participants need to solve a problem based on the extraction of a causal relation between two variables from that graph, referred to as the "department store" task, or the DS task (Pala & Vennix , 2005; Sterman, 2010; Cronin et al, 2009). Cronin and Gonzalez (2007) have pointed out the importance of discovering, on one hand, how people are actually encoding stock and flow problems, and, on the other hand, ruling out the perceptual difficulties related to the interpretation of graphs from the inherent difficulties in understanding stocks and flows. Recently, some authors (Fischer & Degen, 2012 and Hämäläinen et al., 2013) have challenged the use of graphical tasks in assessing understanding about causal relations within the accumulation process, claiming that it is the task design that makes the task difficult to solve. Hämäläinen and his colleagues (2013) draw attention to the wrong cognitive heuristics that might arise from the department store task, whilst Fischer& Degen (2012) argue for a bias in task format that leads to different results when removed. In both cases, giving people a simpler version of the task (Hämäläinen et al., 2013), or simply asking them to explicitly state the relation between the flow and stock (Fischer& Degen, 2012), has led to different, better, results than the initial studies.

Our aim is to further investigate the nature of understanding accumulation principles, and therefore need a definition. We argue that *understanding the accumulation principle* contains one necessary and sufficient condition: *having a correct representation of the causal relations between the system parts,* i.e., the stock and the flows. Correct representation in turn means knowing that "the stock rises if the inflow exceeds the outflow" (Cronin, Gonzalez & Sterman, 2009). Note that this condition is purely global and ordinal in nature. Specifically, understanding refers only to the interaction of the system parts, and does not require the problem solver to calculate any numerical outcome of the system. Suffice to say that if an ordinal relationship is established between the two variables, albeit a relationship denoting a certain position in a sequence, then the solution to the problem is known: if inflow is bigger than the outflow, the stock increases.
A further distinction we make is between information processing, on one hand, which is the cognitive process by which one gets to the understanding of a relation - below described as type of visual search (local vs global) - and the type of information retrieved, which can be ordinal or categorical, albeit of or relating to a category.

Type of visual search and type of information

In investigating the nature of understanding when solving accumulation tasks, we differentiate between type of visual search and type of information retrieved.

The first dimension, *type of visual search*, refers to whether people search texts or graphs in a *local* or in a *global* manner. With a *local*, data-driven search, people attempt to find specific information within a given set of information, or attempt to identify the highs and lows on a graph. With a *global* search, people formulate higher order interpretations, try to get the gist of documents, identify relationships, form a mental model that is useful for problem solving (Wainer, 1992, Mayer, 1992), perceive general trends in a bar graph (*Sanderson et al, 1989*), or extract a rule based on the basic data displayed (Guthrie et al. 1993). In a day to day analogy, global search would mean seeing the forrest, whilst local search would mean looking just for the trees.

The second dimension, *type of information retrieved*, refers to whether people extract *categorical* or *ordinal* information from texts or graphs. We refer to information as categorical, if it is measured on a categorical scale (e.g., "This bar chart represents the amount of sold cars"). We refer to information as ordinal , if it is expressed on an ordinal scale level (e.g., "The amount of cars sold in March is higher than in April"). This distinction is especially relevant in the case of accumulation, where one basic piece of knowledge that is necessary to understand a simple one stock system is the ability to calculate the difference between inflow and outflow (Saldarriaga, 2011), albeit identify which one is bigger (ordinal information) in order to see whether the stock is increasing, decreasing or staying the same.

Note that both dimensions can refer to both the type of task and the type of visual search participants perform. In most cases, the tasks and visual search will be correlated, however, in that different tasks induce different search processes. For example, it was shown that with local questions ("Where is the hammer located?", "How many American-made cars were sold in June of 1989?"), people form more specific categories, whereas with global questions ("What is the pattern of US vehicle sales over the course of one year?", "Why is the oval window located in the canter of the ear?"), people form more simple and complex abstractions (Guthrie et al., 1993). We expect a similar connection to exist for the type of information-retrieved. That is, we expect categorical (ordinal) questions to be more likely to induce categorical (ordinal) responses.

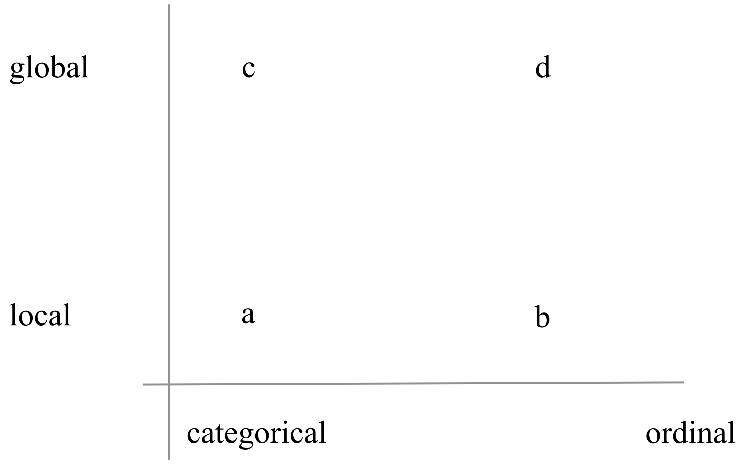


Figure 1. The two dimensions, *type of visual search* and *type of information retrieved* can be combined to make four different types of tasks and problem-solving styles: local-categorical (a), local-ordinal(b), global-categorical (c) and global ordinal (d)

We claim that global (local) search and information retrieved are independent in that any four logically possible combinations can occur (see Figure 1). That is, tasks may be designed to ask for local and categorical information (e.g. «What is the value of emissions around the year 2020?»), for global and categorical («In the following sentences, the two parts of the sentence are logically equivalent . Please fill in the gaps: "CO2 Emissions" is to "CO2 in atmosphere" , as "Savings" is to "………………."? "CO2 Removal " is to "CO2 in atmosphere" , as "……………." is to "Oil reserves"?»), for local and ordinal («In Fig 1, which if the two values around the year 2020 is bigger: emissions or removal?»), and for global and ordinal («What do you think happens to the level of CO2 in the atmosphere if the CO2 emissions level is bigger than the removal?»). Importantly, however, we claim that previous research on SF problems has prompted the subjects with local and categorical tasks. Tasks were designed to lie in this one quadrant, and, as a consequence, this probably also induced a local visual search and and categorical information retrieval in most participants, whilst we claim that the DS task is a global and ordinal one .

To test this claim, in our experiment, we used SF tasks from all four quadrants to investigate the effect of the postulated 2-dimensional task design on performance in SF tasks. Since we argue that a global and ordinal search should be more successful for solving SF tasks, we expect solutions rates to vary as a function of tasks so that b > d = a > c.

Method (see appendix for a description of the tasks)

The participants in this study were 66 university undergraduates from a University of Heidelberg, Germany. The tasks were given as a requirement of a course, and consisted of a common part, in which the subjects were introduced to a CO2 accumulation problem, and then were asked to answer 2 questions. The second question was the same for all the 4 treatments, whilst we varied the first question, which we argue prompts a certain type of visual search, or information type (see the annex for a complete list of tasks). We expected that a global and ordinal prompting task should be more successful for solving a subsequent SF tasks, so we expected solutions rates to vary as a function of this variation, so that

H1: d > b = c > a for the Local/Global dimension
H2: d > c = b > a for the Categorical/Ordinal dimension
where local-categorical is (a), local-ordinal is (b), global-categorical is (c) and global ordinal is (d).

The results are as follows:

Dimensions	categorical	ordinal
local	(a)8 correct, 10 incorrect (44% correct)	(b)8 correct, 10 incorrect (44% correct)
global	(c)9 correct, 5 incorrect (64% correct)	(d)11 correct, 5 incorrect (68% correct)

Overall, the results show that the Global and Ordinal group had the highest number of correct vs incorrect answers.

H1: d>b and c>a
On the first hypothesis, we ran a 2 populations z-test for the local-global dimension , and the result was significant (sig.: $z = 1.81$, $p = .035$), The results indicate that the understanding of accumulation may be global in nature. That is to say, people search for the relationship between the elements in the first question using a global visual search, and thus more readily answer the accumulation question with the same type of search.

H2: d > c = b > a

The categorical-ordinal dimension did not turn out significant : $z = 0.23$, $p = .41$. The second hypothesis could thus not be verified.

Discussion and further research directions

In this article, we argue for a distinction between understanding of the accumulation principle, e.g. how the behaviour of the stock is related to its flows, and failure to apply this information in certain contexts, i.e. solving a problem in which one has to numerically integrate the flows to get the stock level.

Our results indicate that understanding accumulation seems to be better if people are primed to search for the global(forest) than the local (trees) information. We further argue that having a correct representation of the causal relation of the system parts is having a global representation. Accumulation has been mostly studied prompting local search by asking for specific numbers in the task display. Our results propose that this led to an underestimation of people`s understandingof accumulation..

The natural question that arises is then : if people do understand, why do they not use this information? There is abundant research demonstrating that people fail to apply past learning to new situations that share the same causal or mathematical principles (see Gentner et al, 2009), and when people succeed in accessing an appropriate prior example, then they typically perform well in mapping the solution to the current problem (Pirolli & Anderson, 1985; Reed, 1987, 2012). Failure to retrieve and apply information about the relation between two variables for solving a problem, also known as the “inert knowledge” phenomenon, is a major challenge in research on learning, education and conceptual change (Renkl et al, 1996; Barnett & Ceci, 2002; Day & Goldstone, 2012). Further research should investigate whether people may indeed have an understanding of the accumulation principles, yet, that this information may be “inert”, albeit unused in the tasks that researchers have used in their experiments.

Understanding accumulation is a topic that has implications for many areas of research within system dynamics and for the success of policies from environment to working organizations. This research builds on the body of research challenging the view that people do not understand accumulations by further distinguishing what such an understanding entangles, and contributing to the ruling out of perceptual difficulties related to the task itself.

Our study has a limited number of tasks and used students as the main population for the experiment. Further research should replicate the experiment with a larger group, different populations, including practitioners, and introduce different, more complex tasks , to test the hypothesis of a global and ordinal understanding. Another relevant research question is to what degree is global visual search beneficial for the understanding of dynamic systems in general, since such systems cannot be solved analytically when they get too complex.

References

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn?: A taxonomy for far transfer. *Psychological bulletin*, *128*(4), 612.

Confrey, J. (1990). A review of the research on student conceptions in mathematics, science, and programming. *Review of research in education*, *16*, 3-56.

Cronin, M. A., & Gonzalez, C. (2007). Understanding the building blocks of dynamic systems. *System Dynamics Review*, *23*(1), 1-17.

Cronin, M. A., Gonzalez, C., & Sterman, J. D. (2009). Why don't well-educated adults understand accumulation? A challenge to researchers, educators, and citizens. *Organizational Behavior and Human Decision Processes*, *108*(1), 116-130.

Day, S. B., & Goldstone, R. L. (2012). The import of knowledge export: Connecting findings and theories of transfer of learning. *Educational Psychologist*, *47*(3), 153-176.

Fischer, H. & Degen, C. (2012) Stock-flow failure can be explained by the task design, Paper presented at the 30th International System Dynamics Conference, 22-26 july, St Gallen, Switzerland

Gentner, D., Loewenstein, J., Thompson, L., & Forbus, K. D. (2009). Reviving inert knowledge: Analogical abstraction supports relational retrieval of past events. *Cognitive Science*, *33*(8), 1343-1382.

Guthrie, J. T., Weber, S., & Kimmerly, N. (1993). Searching documents: Cognitive processes and deficits in understanding graphs, tables, and illustrations. *Contemporary Educational Psychology*.

Hämäläinen, R. P., Luoma, J., & Saarinen, E. (2013). On the importance of behavioral operational research: The case of understanding and communicating about dynamic systems. *European Journal of Operational Research*.

Okan, Y., Garcia-Retamero, R., Cokely, E. T., & Maldonado, A. (2011). Individual differences in graph literacy: Overcoming denominator neglect in risk comprehension. *Journal of Behavioral Decision Making*, *25*(4), 390-401.

Pala, Ö., & Vennix, J. A. (2005). Effect of system dynamics education on systems thinking inventory task performance. *System Dynamics Review*,*21*(2), 147-172.

Pirolli, P. L., & Anderson, J. R. (1985). The role of learning from examples in the acquisition of recursive programming skills. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *39*(2), 240.

Reed, S. K. (1987). A structure-mapping model for word problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*(1), 124.

Reed, S. K. (2012). Learning by mapping across situations. *Journal of the Learning Sciences*, *21* (3), 353-398.

Renkl, A., Mandl, H., & Gruber, H. (1996). Inert knowledge: Analyses and remedies. *Educational Psychologist*, *31*(2), 115-121

Saldarriaga, M. (2011). Using a water tank analogy to transform students´ intuitive knowledge of dynamic systems. A qualitative study of the case of motion. *Unpublished PhD dissertation,* *University of Bergen, Norway.*

Sanderson, P. M., Flach, J. M., Buttigieg, M. A., & Casey, E. J. (1989). Object displays do not always support better integrated task performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *31*(2), 183-198.

Sterman, J. D. (2010). Does formal system dynamics training improve people's understanding of accumulation?. *System Dynamics Review*, *26*(4), 316-334.

Vosniadou, S., & Kyriakopoulou, N. (2006). The problem of metaconceptual awareness in theory revision. In *Proceedings of the 28th annual conference of the Cognitive Science Society* (pp. 2329-2334). Sun, R. and Miyake, N.

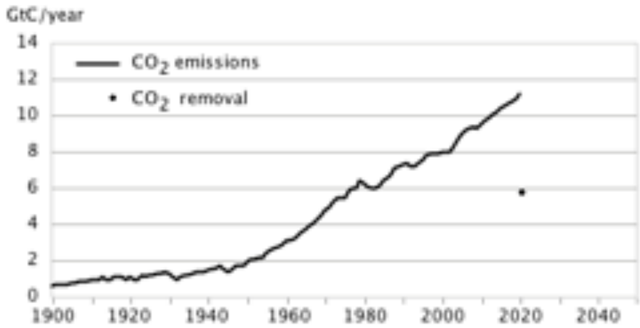
Zuckerman, O. (2007). Flowness + FlowBlocks: Uncovering the Dynamics of Everyday Life through Playful Modeling. *Unpublished PhD dissertation, Massachusets Institute of Technology. USA*

APPENDIX - EXPERIMENTAL TASKS

You have been appointed as CHIEF RESEARCHER for solving the world´s climate problem.

The amount of CO2 in the atmosphere, just the contribution from human activity has been increasing in the past 100 years. The more CO2 in the atmosphere, the more will the climate change.

In the graph below you see how world **emissions** of CO2 have developed from the year 1900 and are likely to develop towards 2020.
Assume that the the quantity of CO2 **removed** from the atmosphere by plants and oceans will be 5.9 billion metric tonnes i all years after 2020 (constant).



CO2 emissions

Local/categorical

Question 1: What is the value of emissions around the year 2020?

Question 2 : Assume that the world politicians wish that the amount of CO2 in the atmosphere remain at the same level as in 2020.

What should the world's CO2 emission be after 2020 to make sure that the amount of CO2 in the atmosphere remains at the same level? Think about it, and write down both your work-out (method) and your answer in billion metric tonnes per year(GtC/year).

Local/ordinal

Question 1: In Fig 1, which if the two values around the year 2020 is bigger: emissions or removal?
(Q2: the same as above)

Global/categorical

Question 1: In the following sentences, the two parts of the sentence are logically equivalent (example: “You” are to “your mother”, as “your mother” is to “your grandmother”). Please fill in the gaps:

“CO2 Emissions” is to “CO2 in atmosphere” , as “Savings” is to “....................”?
“CO2 Removal “ is to “CO2 in atmosphere” , as “..................” is to “Oil reserves”?
(Q2: the same as above)

Global/ordinal

Question 1: What do you think happens to the level of CO2 in the atmosphere if the CO2 emissions level is bigger than the removal?
(Q2: the same as above)