Why Don't Well-Educated Adults Understand Accumulation?

A Challenge to Researchers, Educators, and Citizens

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ABSTRACT

Accumulation is a fundamental process in dynamic systems: inventory accumulates production less shipments; the national debt accumulates the federal deficit. Effective decision making in such systems requires an understanding of the relationship between stocks and the flows that alter them. However, highly educated people are often unable to infer the behavior of simple stock-flow systems. Poor performance has been ascribed to artifacts including complex information displays, lack of contextual knowledge, the cognitive burden of calculation, or the inability to interpret graphs. Here, we demonstrate that poor understanding of accumulation, termed *stock-flow failure*, is more fundamental. In a series of experiments, we find that persistent poor performance is not attributable to an inability to interpret graphs, contextual knowledge, motivation, or cognitive capacity. Rather, stock-flow failure is a robust phenomenon that appears to be difficult to overcome. We discuss the origins of stock-flow failure and implications for management and education.

Keywords: Dynamic decision making, problem representations, accumulation, stocks and flows, system dynamics

INTRODUCTION

Understanding and managing stocks and flows (SF)—that is, resources that accumulate or deplete and the flows that alter them—is a fundamental process in society, business, and personal life. At the macroeconomic level, for example, exploration increases known petroleum reserves, while oil production reduces the stock of oil remaining for the future. In turn, petroleum combustion increases the stock of carbon dioxide in the atmosphere and contributes to global warming. At the organizational level, firms' capabilities and competitive advantages arise from the accumulation of resources and knowledge (Dierickx & Cool, 1989; Sterman, 1989b). Firms must manage their cash flows to maintain adequate stocks of working capital, and production must be adjusted as sales vary to maintain sufficient inventory. Individuals, too, face similar stock management challenges: We manage our bank accounts (stock of funds) to maintain a reasonable balance as our incomes (inflows) and expenses (outflows) vary, and we struggle to maintain a healthy weight by managing the inflow and outflow of calories through diet and exercise. Accumulation is a pervasive process in everyday life, and arises at every temporal, spatial and organizational scale.

All stock-flow problems share the same underlying structure. The resource level (stock) accumulates its inflows less its outflows.[1] Though the relationship between stocks and flows is a fundamental concept of calculus, knowledge of calculus is not necessary to understand the

[1] Formally, the stock at any time T, S_T is the integral of its net inflow, which, in turn, is the inflow, I, less the outflow, O (plus the initial quantity):

$$S_T = \int_{t_0}^{T} Net\ Inflow\ dt + S_{t_0} = \int_{t_0}^{T} (I - O) dt + S_{t_0}$$

Equivalently, the rate of change of the stock is the net inflow:

$$\frac{dS}{dt} = Net\ Inflow = I - O$$

concept of accumulation and the behavior of stocks and flows. Any stock can be thought of as the amount of water in a tub. The water level accumulates the flow of water into the tub (the inflow) less the flow exiting through the drain (the outflow). The rate of change in the water level is the net flow, given by the difference between the inflow and outflow. As everyday experience suggests, the water level rises only when the inflow exceeds the outflow, falls only when the outflow exceeds the inflow, and remains the same only when the inflow equals the outflow.[2]

Prior work has shown that stock-flow problems are unintuitive and difficult, even in simple systems and even for highly educated people with strong technical backgrounds, including calculus (Cronin & Gonzalez, in press; Sterman & Booth Sweeney, 2002; Booth Sweeney & Sterman, 2000). In one experiment, for example, Booth Sweeney and Sterman (2000) presented highly educated graduate students at an elite university with a picture of a bathtub and graphs showing the inflow and outflow of water, then asked them to sketch the trajectory of the stock of water in the tub. Although the patterns were simple, fewer than half the participants were able to correctly sketch the path of the stock.

Two difficulties contribute to this problem. First, many people find it difficult to recognize the key stock in a given situation and to distinguish between the stocks and the flows that alter them—for example, failing to see that the federal deficit is a flow that accumulates into the national debt or that the number of people in a store is a stock that accumulates the inflow of people entering the store less the outflow of people exiting. Second, many people have difficulty applying the principles of accumulation correctly, failing to grasp that the quantity of any stock,

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[2] In general, there may be many inflows and outflows to a stock. For example, the number of employees in a division of a firm can be increased by hiring and transfers into the division, and decreased by quits, transfers out, layoffs, and retirements.

such as the level of water in a tub, rises (falls) when the inflow exceeds (is less than) the outflow. Rather, it appears that people often use intuitively appealing heuristics such as assuming that the output of a system is positively correlated with its inputs. That is, people assume that the output (the level of water in a tub) should “look like” the input (the flow or net flow of water into the tub). We denote such behavior the *correlation heuristic*.

Correlational reasoning can be useful and adaptive (e.g., illness is highly correlated with the consumption of certain mushrooms), but the correlation heuristic fails in systems with significant accumulations. For example, the US federal deficit and national debt have both risen dramatically in the past half century, and they are highly correlated ($r = 0.80$ for annual data from 1950 to 2005, $p < .001$). However, because the debt is a stock that accumulates the deficit, the national debt will continue to rise even if the deficit falls—the debt can fall only if the government runs a surplus. Similarly, birth rates have been falling around the world, but world population continues to grow even as births decline. Population will stabilize only when births fall enough to equal deaths.

As these examples suggest, correlation heuristics can lead to erroneous judgments in situations that have important public policy implications. For example, anthropogenic greenhouse gases are now emitted at roughly double the rate at which they are removed from the atmosphere by natural processes (Houghton et al. 2001). Therefore, atmospheric greenhouse gas concentrations will continue to rise even if emissions fall, until emissions fall to the rate at which greenhouse gases are removed from the atmosphere. However, experiments show that the vast majority of highly educated adults assume that greenhouse gas concentrations follow the same pattern as emissions, leading them to conclude, erroneously, that atmospheric greenhouse gas concentrations can be stabilized even as emissions into the atmosphere continuously exceed removal from it (Sterman and Booth Sweeney, 2006). Such beliefs are analogous to the assertion that a bathtub continuously filled faster than it drains will never overflow. They violate conservation of mass and lead to the erroneous conclusion that the risks of harmful climate change can be mitigated simply by slowing the growth of emissions.

What we do not yet know is why people are so often unable to relate the behavior of stocks to their flows (denoted here as *SF failure*). Although the results of prior work suggest that poor performance arises from the use of the correlation heuristic (Cronin & Gonzalez, in press; Sterman & Booth Sweeney, 2002; Booth Sweeney & Sterman, 2000), there are many other explanations. Perhaps people understand the concept of accumulation but perform poorly because of complex information displays, the cognitive burden of the calculations required to determine the level of the stock, inadequate motivation, unfamiliar or inappropriate task context, or the inability to interpret and construct graphs. If so, it should be relatively easy to induce good performance through the use of appropriate information displays and relevant, familiar contexts, or by training participants in the interpretation of graphs. If, on the other hand, SF failure is a more fundamental limitation of our mental models and cognitive capabilities, it will be robust to such manipulations.

Understanding the sources of SF failure has important theoretical and normative implications. First, it will help improve our understanding of human cognition. If the problem is simply attributable to unfamiliar or poorly designed information displays, then improvement should be a straightforward matter of proper information system design. If, however, the problem is robust to these surface features of the task, the source of the problem may lie in deeper cognitive structures, analogous to the difficulties people have in probabilistic judgment and decision making (Dawes, 1988, 1998; Kahneman & Tversky, 1972). Second, a better understanding of SF failure can inform the design of curriculum and pedagogical methods aimed at improving people's ability to recognize SF structures and infer the relationships among them, thus improving decision quality.

Here, we investigate the robustness of SF failure. We seek to understand why SF failure occurs and what might be done to mitigate it. A series of five experiments investigates the explanations for poor performance identified in prior work. These experiments demonstrate that poor performance persists across multiple information displays, contexts, computational requirements, allowed times, and motivation conditions. Neither skill in interpreting graphs nor the cognitive load of the task appears to be a bottleneck to performance. Poor performance persists regardless of whether the data are presented in text, tabular, or graphic form, across many levels of complexity, and across different degrees of motivation. The results suggest that SF failure is the result of poor ability (1) to recognize the stock and flow structure of a situation and (2) to apply the principles of accumulation correctly.

The remainder of the paper proceeds as follows: We describe prior work and review the literature in the context of a simple stock-flow problem. Next we present the experiments, which address the cognitive burden of the task, information display, task context, motivation and feedback, cue availability, and priming of prior stock-flow knowledge. We consider limitations and extensions, discuss the managerial and educational implications of the results, and offer suggestions for further research to create interventions that may overcome SF failure.

A SIMPLE STOCK AND FLOW PROBLEM

Prior work in dynamic decision making suggests that people have great difficulty understanding and managing systems with high levels of dynamic complexity. Dynamic complexity arises from the presence of multiple feedback processes, time delays, nonlinearities, and accumulations (Sterman, 2002). Furthermore, learning in dynamic systems is often slow and weak, even with repeated trials, unlimited time, and performance incentives (Diehl & Sterman, 1995; Kleinmuntz & Schkade, 1993; Paich & Sterman, 1993; Sterman, 1989a, 1989b). Many of these studies involved tasks of great complexity, and poor performance was often ascribed to the opacity of the system, the large number of entities and interactions, feedback delays, and information overload (Brehmer, 1990, 1995; Gonzalez, 2004; Kleinmuntz, 1985; Omodei & Wearing, 1995). More recent work, however, has shown that people make persistent mistakes even in the simplest dynamic systems consisting of one stock, one inflow, and one outflow, with no feedback processes, time delays, or nonlinearities (e.g., Booth-Sweeney and Sterman, 2000; Sterman & Booth Sweeney, 2002).

To illustrate, the “department store” task presents participants with a graph showing the number of people entering and leaving a department store each minute over a 30-minute interval (Figure 1). The system involves a single stock (the number of people in the store) with one inflow (people entering) and one outflow (people exiting). There are no feedbacks, time delays, nonlinearities, stochastic events, or other elements of dynamic complexity that proved difficult in prior research. Participants are asked four questions. The first two questions—When did the most people enter the store? When did the most people leave the store—test whether participants can read the graph and correctly distinguish between inflow and outflow. The third and fourth questions—When were the most people in the store? When were the fewest people in the store—test whether participants can infer the behavior of the stock from the behavior of the flows.

To do so, one could manually accumulate the stock by finding the net inflow at each point of time and then adding the numbers for each time period. This method, however, is tedious, error prone, and unnecessary. One need only understand that the number of people in the store rises when the flow of people entering is greater than the flow of people leaving (and vice versa), then note that the number entering is greater than the number exiting through time 13 and less thereafter. Therefore, without making any calculations, one can see that the most people are in the store when the two curves cross (Minute 13). Furthermore, because the number of people in the store rises through Minute 13 and falls thereafter, the fewest people are in the store either at the beginning or the end of the 30 minutes. To determine which, participants must judge whether more people (net) enter up to Minute 13 than leave afterward. Once again, calculation is unnecessary: One can simply judge whether the area between the rate of entering and the rate of leaving up to Minute 13 is greater or smaller than the area between the two curves from Minute 14 on. The area between the curves from minute 14 on is clearly larger, so the fewest people are in the store at the end of the 30 minutes. It might be objected that judging the areas of the irregular shapes defined by the difference between inflow and outflow in figure 1 is difficult. However, the task was carefully designed to make the determination of the area simple. The area of the region in which outflow exceeds inflow (after t = 13) was constructed to be twice as large as the area in which inflow exceeds outflow (prior to t = 13). To test whether people can determine which area is larger, a convenience sample consisting of 12 members of the support staff from the MIT Sloan School of Management were asked which area was greater; all correctly identified the larger area.

Insert Figure 1 here

Finally, note that people who do not understand the intuitive concepts of accumulation—that the stock rises when inflow exceeds outflow, and vice versa—can always answer correctly by simply keeping a running total of the number of people in the store, $S_t = S_{t-1} + I_t - O_t$.

Method

A total of 173 students enrolled in a graduate course in business simulation at the MIT Sloan School of Management were asked to answer simple questions about the department store task in Figure 1. Participants were primarily MBA students and graduate students from other MIT departments or from Harvard University. All had taken calculus, and most had strong mathematics training: 71% had a degree in engineering, mathematics, or the sciences; 28% had a degree in the social sciences, primarily economics. Fully 40% had a prior graduate degree, most in technical fields. Students did the task in class at the beginning of the semester. Students were given approximately 10 minutes. Participation was voluntary. Students were informed that the results would not be graded but illustrated important concepts they were about to study and would be used anonymously in this research. To test for order effects, half the participants were randomly selected to receive the questions about the flows (1 and 2) first (Order O1), as shown in Figure 1, and half received the two questions about the stock (3 and 4) first (Order O2).

Results

Table 1 summarizes the results of the department store task.[3] Question order made no difference. (Using Fisher's exact test to compare whether the order of presentation affected the number answered correctly on each question, the p levels for Questions 1–4 were 0.44, 0.17, 1.0, and 1.0, respectively). Hence, we pool O1 and O2 in the results presented here. The vast majority of participants correctly identified when the most people entered and left the store (96% and 95% for Questions 1 and 2, respectively). However, few were able to answer the stock-flow questions

[3] Answers to all questions were considered correct if they were within 1 minute of the correct response, that is, responses of 12, 13, or 14 were coded as correct responses to the question "During which minute did the most people enter the store?" These tolerances count as correct those who understood the concepts but might have misread the time-axis values, favoring high performance.

correctly (44% and 31% for Questions 3 and 4, respectively). About 17% indicated that it is not possible to determine when the most people were in the store, and 25% said that it is not possible to determine when the fewest people were in the store. Many participants appear to assume that the stock should match the inflow or the outflow, leading them to make erroneous inferences about the stock (see Sterman, 2002, for a discussion). To illustrate, 29% incorrectly indicated that the most are in the store when the net inflow is greatest (t = 8) and 30% incorrectly indicate that the fewest are in the store when the net outflow is greatest (t = 17). These responses, accounting for far more of the erroneous choices than any other, reveal a fundamental confusion about the relationship between stocks and flows. The belief that the extreme values of the stock coincide with extremes of the net inflow violates the most basic relationships between stocks and flows.

Insert Table 1 here

Why is this the case? Is the difficulty that people exhibit in SF tasks (such as the department store case) an artifact of the task that could easily be remedied, a limitation in education and training, or a manifestation of a more persistent cognitive limitation? The experiments presented here test these hypotheses and suggest avenues for research to discover improved methods to present, learn about, and understand the structure and dynamics of accumulation.

In all of the experiments, participants were given a problem involving one stock, one inflow, and one outflow. In all of the experiments, participants were asked to answer the four questions presented in the baseline experiment. Because the baseline condition revealed no order effect, the questions were always presented in the same order (most entering, most leaving, most in store, fewest in store). Unless otherwise noted, participants received as much time as needed (rarely did they need longer than 10 minutes) and were offered no performance-based incentive (except in Experiment 3).

EXPERIMENT 1: COGNITIVE BURDEN AND DATA DISPLAY

Limited cognitive capacity is a commonly cited explanation for poor performance in problem solving (Simon, 1979). In SF systems similar to those studied here, the cognitive burden may arise from the need to manipulate and hold in memory a large set of numbers. Specifically, individuals might attempt to answer the SF questions by calculating the accumulation of people in the store each minute. To do so participants must first find the numerical value of the flow of people entering and leaving the store by reading the graph, then subtract the outflow from the inflow to compute the net flow, and finally, add the net flow to the running tally of the stock stored in memory. The baseline task in Figure 1 presents 60 data points (inflow and outflow data for 30 minutes), perhaps overwhelming participants' available cognitive capacity and working memory. Therefore, we created a simpler version of the problem, shown in Figure 2A. The pattern is similar to that of the baseline condition but presents data for only 12 minutes, and the value of the flows never exceeds 15 people per minute (compared to nearly 40 people per minute in the baseline task). We retained the key features of the baseline task: The number of people in the store rises, peaks, and falls. The most people are in the store at $t = 7$, and the fewest are in the store at the end ($t = 12$). The cumulative number of people leaving after the store population peaks is twice as large as the number entering before the peak. If cognitive capacity is a source of error, then performance in the simpler version should improve compared to the baseline. If, on the other hand, the difficulty arises from a weak understanding of the concept of accumulation, then performance in the simpler version should not improve. Hence,

H_1: Performance will improve in simpler versions of the task with fewer data points.

Another common explanation for poor problem solving is confusing information presentation. To test this possibility, we created three isomorphs of Figure 2A: a bar graph, a table, and a textual presentation (see Figures 2B–D). Researchers have shown that many people have difficulty interpreting graphs (Paulos, 1988). If people misread the graph, they are likely to answer the questions incorrectly as well. The high performance on Questions 1 and 2 suggests that participants in the baseline condition (MIT graduate students) were able to read the graphs. Nevertheless, perhaps the use of a graphical display makes it difficult to appreciate the accumulation of people in the store. If the ability to interpret graphs is the source of the difficulty, then an alternate data presentation mode, such as a table or text, should improve performance on the stock-flow questions.

Insert Figures 2A–2D here

$H_{2.1}$: Performance will improve if the data are presented in tabular or textual form rather than in graphic form.

Another possibility is that the *form* of the graph leads people to misinterpret the problem. Kotovsky, Hayes, and Simon (1985) showed that problem solving is more difficult when people cannot reconcile the formulation of a problem with their beliefs about the real world. They used a puzzle similar to the Tower of Hanoi in which acrobats jump from one stand to another, sometimes coming to rest on each other's shoulders. Participants were given isomorphic puzzles (with the same rule structure, moves, and solution space). For one group, larger acrobats could not jump onto smaller acrobats' shoulders, and in the other group, smaller acrobats could not jump onto larger acrobats' shoulders. The latter group had more difficulty solving the puzzle, presumably because what they saw conflicted with their belief that smaller people could not hold larger ones.

A similar conflict may be at work in SF problems. The information in Figures 1 and 2A is presented using a line graph. Line graphs are often used to represent continuously varying quantities, such as water flowing into a tub. Here, however, the data points represent the total number of people who entered or left over the course of each minute, not the instantaneous rate at which people were entering or leaving at each moment. The continuous flow metaphor suggested by the line graph may conflict with participants' conception of the discrete event of a person entering or leaving a store. Bar graphs are more commonly used to represent totals over some finite period and may help people recognize and understand the relationship between the flows and the stock. Hence,

> **$H_{2.2}$**: People will be more successful at judging the behavior of stocks and flows when discrete quantities are represented with discrete features (bars instead of lines).

Comparing the table to a textual presentation (Figure 2C versus Figure 2D), participants should find a numeric table more helpful than a paragraph because the numbers are already aligned, reducing the cognitive burden involved in finding the values of the inflow and outflow and calculating the net flow. Hence,

> **$H_{2.3}$**: Performance should improve when the data are presented in a table compared to text.

Method

Participants (*N* = 271) were students enrolled in a subsequent term of the same course in business dynamics at the MIT Sloan School of Management used in the baseline experiment. The average age was 29 (range 18–38), and 69% were male. Of the participants, 55% were trained in engineering, mathematics, or the sciences; 38% were trained in economics or another social science; and 29% held prior advanced degrees. Participants were randomly assigned to one of the four data presentation modes shown in Figure 2. Participants were demographically similar to those who participated in the baseline experiment in gender, age, prior education, and prior advanced degrees. As in the baseline, responses were considered correct if they were within 1 minute of the correct answer, a procedure that favors high performance.

Results

We first consider differences across data display modes (Hypotheses 2.1–2.3). Table 2 compares performance across the four isomorphic data presentation modes. Block A compares performance in the two graphic conditions (line and bar) to the two nongraphic conditions (table and text). Contrary to the hypothesis that SF failure is the result of participants' inability to interpret graphs, graphic presentation appears to reduce errors in data interpretation. Performance on Questions 1 and 2 was significantly higher for the graphic representations than for the nongraphic conditions (p = .015 and .001, respectively). There is also no support for the hypothesis that participants' poor ability to interpret graphs is responsible for their poor understanding of accumulation. Contrary to Hypothesis 1.1, performance on the two stock-flow questions was no better in the graphic conditions than in the nongraphic conditions.

Insert Table 2 here

There was no significant difference between the line and the bar graph representations (Table 2, Block B). Performance on the stock-flow questions was slightly better in the bar graph condition, but the differences were not significant (69% in the bar graph condition correctly identified when the most are in the store compared to 52% in the line graph condition, $p = .07$), and only for Question 3 (there was no difference on Question 4). At best, there is only weak support for Hypothesis 2.2: Participants did not appear to be confused by the presentation of the data in the line graph format, which suggests continuous flows, compared to the bar graph format, which suggests discrete flows.

There also was no difference between the tabular and textual presentations on any of the questions (Block C). Only one participant in the text condition made a graph from the data, although the graphic display of the data would have allowed a direct determination of the stock-flow questions without calculation. None of the participants in the table condition made a graph.

Turning now to the issue of cognitive overload, Block D in Table 2 compares the performance of participants who received the simple line graph condition (Figure 2A) to the baseline experiment (Figure 1).[4] Results are similar to the baseline. Participants generally interpreted the data correctly: Performance on Questions 1 and 2 was high, but participants did poorly on the stock-flow questions. Individuals receiving the simpler version did no better than those receiving the baseline condition. Like the baseline, many participants in the line graph condition indicated that the answer to the stock questions could not be determined (21% and

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[4] Because the baseline task in Figure 1 and the simpler tasks in Figure 2 were administered to students taking the same class in successive years, it is possible that there are unmeasured sources of variation that could confound the interpretation of the results. However, the tasks were administered to each group by the same instructor (JS), in the same course, at the same point in the semester, in the same classroom, at the same time of day, and with the same instructions and time for completion. There were no significant differences in the demographic characteristics of the

27% for Questions 3 and 4, respectively, compared to 17% and 25% in the baseline; p = .44, .86). Thus, Hypothesis 1 is not supported: The simpler version of the task with far fewer data points did not improve performance on the stock-flow questions.

One may argue that, although the simplified graph, with its 12 rather than 30 minutes of data, reduces the mental burden of the task, it still overwhelms participants' cognitive capacity. However, even simpler versions with still fewer data points and even simpler patterns did not improve performance. To illustrate, Figure 3 shows an extremely simple pattern with both the number of people entering and leaving the store rising linearly over 5 minutes (Cronin & Gonzalez, in press). Though participants had no difficulty answering Questions 1 and 2 correctly (97% on both), performance on the stock-flow questions was low (most in store, 33%; fewest in store, 37%), similar to the baseline experiment (participants, N = 35, were a mix of undergraduate and graduate students at Carnegie Mellon University). These results argue against the hypothesis that cognitive overload causes poor performance.

Insert Figure 3 here

Overall, the results of Experiment 1 do not support the hypotheses that cognitive capacity, the ability to interpret graphs, or the mode of information display cause poor performance in stock-flow systems.

EXPERIMENT 2: TASK CONTEXT

Another explanation for SF failure is that the task context or cover story does not activate the participants' stock-flow knowledge—people may understand the principles of accumulation

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two groups. Nevertheless, we alert the reader to the possibility that the results could reflect unmeasured sources of variability across the two groups.

but are unable to recognize the stock and flow structure of the situation. Problem framing and task context can significantly change people's decisions (Tversky & Kahneman, 1986) and decision processes—for example, people tend to make different decisions when a choice is framed as a monetary gamble or a jury verdict, even when the two problems have the same probability structure (Rettinger & Hastie, 2001). The cover story may bring some knowledge into working memory while other knowledge remains latent. For example, it is possible that even people who have studied calculus may not recognize the stock-flow structure of the department store context. However, they might be able to do so if the context were more familiar or involved fewer distractions (e.g., When did the store open? What do the people do in the store? What time of day is it?).

Therefore, we created two additional cover stories for the original baseline task outlined in Figure 1. In the *tub condition,* the data represent the flow of water into and out of a bathtub, and the stock is the quantity of water in the tub. In the *cars condition,* the data represent the velocities of two cars traveling in the same direction; the stock is the distance between them.

We hypothesize that the likelihood of activating the stock-flow schema depends on the salience and familiarity of the accumulation process in the task context. People are likely to have more experience and familiarity with bathtubs and driving than with the flow of people into and out of a store. Accumulation is the purpose and focus of attention when filling a container, and people can directly observe the flows and water level. Similarly, monitoring the distance between vehicles is a central task in driving, and the speed and distance between cars are directly observable. In contrast, the flows of people into and out of a store and the population of people within it are not typically observable in everyday experience. If salience and familiarity are important in activating participants' latent stock-flow knowledge, then performance in the tub and driving conditions should be better than in the store condition.

> **$H_{3.1}$**: People will make better judgments of a stock's behavior when the context is more familiar and the stock is more salient, implying better performance in the tub and cars conditions than in the store condition.

The activation of latent stock-flow knowledge may also depend on whether the cover story involves discrete events or continuous flows. Common examples of accumulation used in high school mathematics and physics classes, for example, involve continuous quantities and flows, such as water filling a tank or velocity accumulating into distance traveled. The store context, however, involves discrete, unique individuals entering and leaving at particular moments, which may prevent participants from recognizing the stock-flow structure. Both the tub and cars conditions involve continuous quantities that evolve in continuous time. If the correspondence of the cover story to a schema of accumulation that involves continuously varying flows is important to participants' ability to recognize the stock and flow structure of the problem, then performance in the tub and car conditions should also exceed performance in the store condition.

> **$H_{3.2}$**: People will be better able to judge the behavior of the stock when the stock represents a continuous rather than a discrete quantity, implying better performance in the tub and cars conditions than in the store condition.

Method

We recruited 47 undergraduate students from Carnegie Mellon University who participated voluntarily and received $5.00 compensation for their time. The average age was 25.

No gender information was collected in this case. Participants were randomly assigned to the tub, cars, or store condition.

Results

As in prior experiments, this population showed excellent ability in reading the graph (Table 3), with 96% and 94% correctly answering Questions 1 and 2, respectively. Also consistent with prior conditions, performance on the stock questions was poor (28% and 26% for Questions 3 and 4, respectively). There were no statistically significant differences in performance on the stock questions across the different task contexts. Furthermore, success rates on Questions 3 and 4 remained less than 38%. Thus, neither Hypothesis 3.1 nor 3.2 is supported: Participants' poor ability to relate flows to the stock does not appear to be an artifact of the context. The more familiar tub and driving contexts, with their continuously varying flows rather than discrete individuals, do not appear to improve performance.

Insert Table 3 here

EXPERIMENT 3: MOTIVATION AND FEEDBACK

Another explanation for SF failure is that people do not think much about their answers. In the baseline task shown in Figure 1 and in some prior research (Booth Sweeney & Sterman, 2000), no incentives were offered for performance, perhaps reducing motivation and effort. As Petty and others (Petty & Caccioppo, 1986; Petty & Wegener, 1998) have shown, people who do not have a reason to think hard about a problem will rely on simple heuristics to make judgments instead of solving problems analytically or challenging the appropriateness of the commonsense approach.

We expect that participants are more likely to use heuristics that do not account for stock-flow structure, such as the correlation heuristic, when they are not motivated to think hard about their answers. Although individuals may realize that calculating the net change in the stock and accumulating it manually for each time period will yield the answer, they may choose not to do so. Similarly, with low motivation, people may devote insufficient cognitive effort to the examination of the problem and fail to notice the stock and flow structure. Prior work (Sterman & Booth Sweeney, 2002; Booth Sweeney & Sterman, 2000) has shown that many people assume the output of a system (here, the stock) is correlated with the input (here, the inflow or net flow). With low motivation, people may simply use a heuristic based on matching the pattern of the flows. Such a heuristic yields an answer—albeit an incorrect one—quickly and with little effort. In contrast, high motivation should encourage greater cognitive effort, increasing the probability that participants will recognize the stock-flow structure and use their understanding of accumulation to derive the correct answer. Even if some participants fail to grasp that the stock rises when inflow exceeds outflow and falls when outflow exceeds inflow—which would allow them to answer correctly without calculation—higher motivation should lead more participants to calculate the running total store population, improving performance even if they do not understand the nature of accumulation.

$H_{4.1}$: High motivation will improve performance on the stock-flow questions.

Low motivation may also lead people to fail to check their answers, resulting in careless mistakes. If so, feedback on their initial responses might motivate participants to devote additional cognitive effort to the task, increasing the likelihood of activating their latent understanding of stock-flow knowledge. Motivation to think more about a wrong answer should also eliminate answers that are wrong but plausible.

$H_{4.2}$: Feedback that alerts participants to mistakes will improve performance on subsequent attempts.

Method

We recruited two groups of undergraduate students from the George Mason University School of Management, all of whom participated for course credit. Group 1 ($N = 32$) received the motivation/feedback condition. The average age of this group was 22 (range 19–45), and 51% were male. Group 2 ($N = 37$) received the no motivation/no feedback condition. The average age of this group was 24 (range 19–50), and approximately 45% were male. Participants in both conditions received the standard protocol for the task outlined in Figure 4 and were given up to one hour to complete the task.

Insert Figure 4 here

In the no motivation/no feedback condition, participants only had to answer the four questions and received no performance-based reward. In the motivation/feedback condition, participants were instructed to answer the four questions and then bring their papers to the experimenter to find out whether their answers were correct. Incorrect responses were marked wrong, but no other information was provided. The participants returned to their seats with the same graph to correct their response(s). Participants then turned in their sheets to the experimenter and again received feedback. Participants continued this process until they answered all four questions correctly. Motivation was induced by informing participants that they could leave the session once they answered all questions correctly or after one hour, whichever came first. Participants normally spend less than 10 minutes answering the four questions (which was also true for the no motivation/no feedback group), so those answering correctly could save the bulk of an hour, motivating them to do well on the first attempt.

The effect of motivation was assessed by comparing the performance of those in the no motivation/no feedback condition to the performance of those in the motivation/feedback condition on the first attempt (between participants). The effect of feedback was assessed by comparing the percentage of people in the motivation/feedback condition who answered the question correctly on the first try to the percentage of those who answered correctly on the second try after receiving feedback (within participants).

Results

Results for participants' first attempt are similar to prior conditions: Nearly all of the participants read the graph correctly on their first attempt (94% and 97% for Questions 1 and 2, respectively; see Table 4A), but very few answered the stock-flow questions correctly (16% and 13% for Questions 3 and 4, respectively). Thus, performance on the stock-flow questions was poor in both conditions, and the differences in performance between the two conditions were not statistically significant for either the graph interpretation questions (1 and 2) or the stock-flow questions (3 and 4) . Motivation did not significantly improve performance on the first trial for the stock-flow questions. Therefore, Hypothesis 4.1 not supported: Poor performance does not appear to be caused by low effort.

Turning to the impact of feedback, although feedback did eventually improve performance, we saw no indication that the stock-flow errors were simple, easily correctable mistakes. The number of participants who answered the stock-flow questions correctly rose slowly: Only 28% and 25% correctly answered Questions 3 and 4, respectively, on the second attempt, and by the sixth attempt, performance reached 81% and 84%, respectively. There was no further improvement with continued trials; the remainder of the participants were unable to answer the stock-flow questions on the first task by the end of the hour and were dismissed. The mean number of attempts made on the first task before correctly answering both stock-flow questions was 4.6. Table 4B compares participants' performance on the first and second attempts in the motivation/feedback condition. The table reports the success rate for those who failed to respond correctly the first time. For example, of 32 total participants, 5 answered question 3 correctly the first time (16%). Of the remaining 27 participants, 4 answered correctly on the second attempt (15%). There is no statistically significant difference in success rates on the stock-flow questions after the participants were given feedback.

Many participants recorded calculations on their papers. Most recorded the net flow each minute and a running total of the store population, suggesting that these participants attempted to calculate the number in the store rather than grasping the pattern of relationships between the stock and flows (recall that all questions can be answered without any calculation by applying the basic concepts of accumulation). Table 4C compares the performance of those who recorded calculations to those who did not. People did no better even when they attempted a purely mechanical, calculation method. None of the differences are significant.

Insert Tables 4A–4C here

The first three experiments provide no support for the hypotheses that SF failure is an artifact of information display, the inability to read graphs, the cognitive load of required calculations, unfamiliar or incompatible contexts, poor motivation, or lack of feedback. The results are consistent with the hypothesis that that the difficulty lies in the conceptualization (rather than the execution) of problem solving. Poor performance appears to arise from weak understanding of the concepts of accumulation. The following experiments seek insight into the sources of SF failure—specifically, the erroneous cognitive models that may be created by faulty encoding and interpretation of stock-flow situations.

EXPERIMENT 4: INFERRING FLOWS FROM THE STOCK

So far, all of the tasks required participants to infer the behavior of the stock from the behavior of the flows. Doing so requires people to understand that the stock is the accumulation of the net flow (the running total of inflow less outflow). Next, we test whether people understand that the rate of change in the stock is the net flow into the stock. For example, if the inflow was 20 units during the last minute and the stock increased by 10 units during that interval, then the outflow must have been 10 units. Inferring the flows from the stock might be easier than accumulating the stock from its flows because it does not require people to keep track of the running total or to estimate the area swept out by the difference between the inflow and outflow.

We modified the task so that the behavior of the stock and one of the flows is given and then asked participants to infer the behavior of the other flow. We used the same four questions. When the stock is given, the answers to Questions 3 and 4—When were the most/fewest people in the store?—can be read directly from the graph. When the inflow is given, the answer to Question 1—When did the most people enter the store?—is also given directly. Participants must infer the answer to the remaining question—When did the most people leave the store?—by comparing the net change in the stock to the inflow. Doing so is simple: The change in the stock is $\Delta S_t = I_t - O_t$, so the outflow is given by $O_t = I_t - \Delta S_t$. In the foregoing example, the inflow is 20, but the net change is only 10, so the outflow must be 10. No running total need be estimated or calculated. The situation is analogous when the stock and outflow are given. If the difficulty people have with SF problems arises from their inability to keep a running total of the store population, performance should improve. If, however, the problem is that people do not understand the concept of accumulation, performance will not improve. Hence,

> **H_5**: On graphs showing the stock and one of its flows, success rates in identifying the behavior of the absent flow will be similar to success rates identifying the behavior of the absent stock when both flows are given.

Method

We recruited 30 George Mason University undergraduates, all of whom participated for course credit. Participants were given three simple 5-point graphs (Figure 5A–5C). Figure 5A gives both flows but not the stock (the usual condition), Figure 5B gives the stock and outflow but not the inflow, and Figure 5C shows the stock and inflow but not the outflow. The order of presentation of the graphs was counterbalanced; there was no statistically significant order effect in the results. Participants were asked the standard four questions for each task.

Insert Figures 5A–5C here

Results

Table 5 presents the success rates across conditions. The gray squares indicate the information that could *not* be read directly from the graph. Results for the standard task with the stock missing were similar to prior experiments: Most people read the graph well but did poorly in assessing the behavior of the stock (3% and 10% for Questions 3 and 4, respectively). Performance in the missing flow conditions was similarly poor. In the missing inflow condition, performance on Question 1 was 7%, which was not statistically different from the success rates on Question 3 or 4 in the missing stock condition. Similarly, in the missing outflow condition, performance on Question 2 was 10%, which was not statistically different from the success rates on Questions 3 or 4 in the missing stock condition.

Insert Table 5 here

The results support Hypothesis 5: People have as much trouble inferring the behavior of a stock-flow system when one of the flows is missing as they do when they are asked to determine the behavior of the stock. People's poor performance is consistent with the tendency to use information that is given while overlooking relevant information that is only implied (Fischhoff, Slovic, & Lichtenstein, 1978; Klein, 1999). In the missing flow conditions, the implied relevant information included the net change in the stock, which could easily be calculated from successive values of the stock.

EXPERIMENT 5: DIRECT ACTIVATION OF STOCK-FLOW KNOWLEDGE

Given people's tendency to ignore information that is not explicitly given when making decisions (Fischhoff & Downs, 1997; Ross & Creyer, 1992), bringing relevant but implied information to people's attention should improve performance—if they understand the principles of accumulation. Experiment 4 should have helped because the missing flow condition presents participants with data for both a flow and the stock, while the baseline condition presents only flow data. However, performance did not improve. In Experiment 5, we strengthened the cues designed to activate participants' latent knowledge of stock-flow systems. We used a priming task that explicitly directed participants' attention to the accumulation of the flows into the stock. If people are forced to think about the stock and its accumulation pattern, then their knowledge of accumulation, if it exists, should be activated for subsequent problems. Such direct activation should improve performance in the same way that a hint works in changing peoples' representations in insight problems (Kaplan & Simon, 1990).

> **H_6**: Providing cues to encourage participants to notice the presence and behavior of SF structures will increase their success in understanding the relationship between stocks and flows.

Method

We recruited 37 undergraduate students at George Mason University, all of whom participated for course credit. Their average age was 23 (range 19–44), and 42% were male. Participants were first given a priming task with an extremely simple version of the department store task (Figure 6A). The priming graph shows a constant inflow of 10 people per minute and a constant outflow of 5 people per minute, over an interval of five minutes. Written instructions asked participants to determine how many people are in the store each minute (assuming none were there initially). The explicit direction to record how many are in the store each minute should help participants recognize that the number of people in the store accumulates the inflow less the outflow without explicitly telling people how to do the calculation. The extreme simplicity of the example reduces the cognitive burden of the required calculations. Immediately after completing the priming task, participants were given the simple task shown in Figure 6B and asked to answer the standard four questions.

Insert Figures 6A and 6B here

Results

Overall success rates (Table 6) approximated those observed in the other conditions: high success rates on the first two questions, indicating that the participants could read the graph, and low success rates on the stock questions, indicating that the participants generally did not understand the concepts of accumulation (27% and 38% for Questions 3 and 4, respectively). Success on the stock-flow questions was marginally higher than the baseline for this population (8% and 16% on an isomorphic 5-point graph),[5] so priming did have some effect, partially supporting Hypothesis 6. Yet it by no means eliminated the problem. Surprisingly, nearly half the participants (18 of 37) did the priming task incorrectly; most of these participants responded that the number of people in the store each minute was 5, 5, 5, 5, 5—that is, they gave the net flow of people into the store rather than the total number (5, 10, 15, 20, 25). Those who responded correctly did significantly better on the stock-flow questions in Figure 6B than those who did not: None of those who failed on the priming task correctly identified when the most people were in the store, compared to about half of those who did the priming task correctly (p = .0004). Only one of those who failed on the priming task correctly identified when the fewest people were in the store, compared to 68% of those who got the priming task right (p = .0001).

Insert Table 6 here

The results suggest that many people (about half the participants) did not understand the concept of accumulation. However, even for those who answered the priming question correctly,

[5] Though the baseline graph was given in a different semester, the populations from which all the George Mason University participants were drawn were very similar, as were recruitment methods and the manner (room, time, etc.) in which the tasks were administered. Nevertheless, the same caveat as in note 4 applies.

success rates on the stock-flow questions in Figure 6B remained discouragingly low for such a simple task. Many who could accumulate the net flow of people in the store mechanically in the priming task (Figure 6A) were unable determine when the most and fewest people were in the store in Figure 6B despite the extreme simplicity of that task. It appears that many participants not only had difficulty applying the principles of accumulation but also failed to recognize the stock-flow structure of the task, even after being explicitly directed to carry out the accumulation of inflow and outflow into a stock. The results suggest that for these people, the problem is not the failure to activate knowledge of accumulation but the lack of such knowledge.

GENERAL DISCUSSION

Results from the five experiments reported here demonstrate an important and pervasive problem in human reasoning: our inability to understand stocks and flows, that is, the process by which flows into and out of a stock accumulate over time. Stock and flow structures are pervasive in systems at all scales, from the accumulation of water in a tub to the accumulation of greenhouse gases in the atmosphere. Effective decision making in dynamic settings requires decision makers to understand accumulation. Prior work has demonstrated that even highly educated people do poorly on a range of simple stock-flow problems.

We tested whether people in fact understand the concepts of accumulation, but perform poorly due to information displays, unfamiliar contexts, inadequate motivation, inability to read or construct graphs, or limited cognitive capacity. We found no support for these hypotheses. Poor performance persisted even when the tasks could be done without any calculation, when the number of data points presented was reduced by a factor of six, and regardless of whether the data are displayed in line graphs, bar graphs, tables, or text (Experiment 1). Poor performance was robust to changes in the cover story and to contexts that involved discrete entities or continuously varying quantities (Experiment 2). Modest incentives to respond correctly did not lead to improvement on the first attempt (Experiment 3). The problem persisted regardless of whether people were asked to infer the accumulation of the stock from the flows or the behavior of the flows from the stock (Experiment 4). Many could not correctly accumulate the quantity in the stock even when they were explicitly directed to do so in a problem with constant flows (Experiment 5), and many of those who could had difficulty applying the concepts to a subsequent, highly simplified problem (Experiment 5). Finally, although outcome feedback indicating when participants had provided an incorrect answer did improve performance, the improvement was slow, and a number of people never responded correctly, even after many trials (Experiment 3).

Although most of the experiments allowed participants 10 minutes to finish the task, most of the participants finished much earlier. Many reported high confidence that their answers were correct, even when they were not. In Experiment 3, for example, in which participants were given performance feedback, many participants expressed disbelief when they were told that their answers were incorrect. These behaviors, coupled with the persistence of poor performance in the face of large manipulations in task features, context, and so forth, suggest that SF failure shares some features with insight problems (Mayer, 1995). Insight problems are analytically easy—once one recognizes the proper frame to use. Until then, people tend to use a flawed but intuitively appealing problem frame. Consider, for example, this problem: “A man has married 20 women in town. He has divorced none of them, and they are all still alive, yet he is not a polygamist. How?” This question is challenging only because people assume that the man is married to the women, not that the man performed the marriage ceremony as part of their cognitive representation of the problem.

It seems that people often use the wrong representation to think about the stock and flow structure of the situation and employ heuristics that are intuitively appealing but erroneous—for example, they assume that the output of the system (here, the stock) should be correlated with its inputs (the flows or net inflow). The intuitive appeal of the correlation heuristic appears to be quite strong: Attempts to activate participants' latent knowledge of accumulation through cover stories emphasizing familiar contexts with continuously varying quantities (Experiment 2), through motivation and feedback (Experiment 3), and by explicitly directing people to accumulate a stock prior to doing the task (Experiment 5) had little impact.

The results indicate that two problems contribute to poor performance. First, people have difficulty recognizing the stock in a given situation—in this case, they fail to grasp that the number of people in a store is a stock that accumulates arrivals less departures. If recognizing the stock were the only problem, then helping people attend to the stock would improve performance. However, the results, particularly those of Experiment 5, suggest that for many people, the problem is not merely the failure to recognize the stock but ignorance of the basic principles governing accumulation (the relationships between the flows and the stock over time). Many people fail to grasp that, like any bathtub, the quantity of any stock rises (falls) when the inflow exceeds (is less than) the outflow. For these people, intuitively appealing heuristics such as pattern matching appear to dominate their judgment. Consistent with the results of the baseline experiment reported here, and with Cronin and Gonzalez (in press), people tend to identify the point with the highest inflow (outflow) or the greatest (smallest) instantaneous net difference as the point at which the stock is most full (empty).

The use of inappropriate heuristics and the persistence of error in stock and flow problems, even among highly educated individuals, is reminiscent of the difficulties that people have with probabilistic judgment. Much productive research has come from studying errors in probabilistic reasoning (e.g., Dawes, 1998) and has found broad application in fields such as risk analysis (Kahneman & Tversky, 1979) and negotiation (Bazerman & Neale, 1992). Insight into people's difficulties with dynamic decision making, including stock and flow structures, may yield similar practical benefits, especially in forecasting, operations, strategy, and a variety of important public policy domains.

Understanding the nature of people's errors in stock-flow situations may also inform the study of human cognition. Understanding how individuals set up a problem is a burgeoning area of research (Legrenzi, Girotto, & Johnson-Laird, 1993), and is arguably understudied in cognitive psychology (Simon, 1991). There is little work on the generation of insight in the context of standard problem solving (Cronin, 2004); the class of stock-flow structures may present opportunities to explore the nature of insight in a common and important class of everyday reasoning problems.

The biggest challenge for future work is to find effective methods to improve people's understanding of stock-flow systems. Doing so requires greater insight into the construction and nature of people's mental representations as they try to solve SF problems. The use of verbal protocols, as Chi, Feltovich, and Glaser (1981) suggest, may reveal the deep structure of this class of problems, including other influences that promote or inhibit the discovery of the structural relationship between stocks and flows. Other pedagogical methods should be investigated, including having people work in teams so that those who appreciate stock-flow structures can correct the heuristic errors of others (Heath, Larrick, & Klayman, 1998). The impact of background training in systems thinking and dynamic modeling should also be explored.

Research should investigate the cues that trigger or inhibit the use of the correlation heuristic and the learning processes through which individuals acquire and use the deep structure of the problem. Learning in many domains, including dynamic decision making, often occurs implicitly (Gonzalez, 2005; Gonzalez, Lerch, & Lebiere, 2003; Reber, 1976, 1989): Individuals who do well on a task are not always aware of the task structure, may not be able to describe the key elements of the task, and may be unable to verbalize the ways in which they make decisions, suggesting that the knowledge acquired does not take the form of rules about how the system works. Future research should seek to discover ways in which we can provide individuals with both implicit and explicit knowledge of stock and flow problems, increasing our ability to understand the dynamics of complex systems affecting our personal lives, organizations, and society.

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References

Bazerman, M. H., & Neale, M. A. (1992). *Negotiating rationally.* New York: Free Press.

Booth Sweeney, L., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review, 16*(4), 249–286.

Brehmer, B. (1990). Strategies in real-time, dynamic decision making. In R. M. Hogarth (Ed.), *Insights in decision making: A tribute to Hillel J. Einhorn* (pp. 262–279). Chicago: University of Chicago Press.

Brehmer, B. (1995). Feedback delays in complex dynamic decision tasks. In P. A. Frensch & J. Funke (Eds.), *Complex problem solving: The European perspective* (pp. 103-130). Hillsdale, NJ: Lawrence Erlbaum.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*(2), 121–152.

Cronin, M. A. (2004). A model of knowledge activation and insight in problem solving. *Complexity, 9*(5), 17–24.

Cronin, M. A., & Gonzalez, C. (in press). Understanding the building blocks of dynamic systems: What is the problem, really? *System Dynamics Review.*

Dawes, R. M. (1988). *Rational choice in an uncertain world.* San Diego, CA: Harcourt Brace Jovanovich.

Dawes, R. M. (1998). Behavioral decision making and judgment. In D. T. Gilbert, S. T. Fiske, & G. Lindzey (Eds.), *The handbook of social psychology* (4th ed., pp. 497–538). Boston: McGraw-Hill.

Diehl, E., & Sterman, J. D. (1995). Effects of feedback complexity on dynamic decision making. *Organizational Behavior and Human Decision Processes, 62*(2), 198–215.

Dierickx, I., & Cool, K. (1989). Asset stock accumulation and sustainability of competitive advantage. *Management Science, 35*(12), 1504–1511.

Fischhoff, B., & Downs, J. (1997). Accentuate the relevant. *Psychological Science, 8*(3), 154–158.

Fischhoff, B., Slovic, P., & Lichtenstein, S. (1978). Fault trees: Sensitivity of estimated failure probabilities to problem representation. *Journal of Experimental Psychology: Human Perception and Performance, 4*(2), 330–344.

Gonzalez, C. (2004). Learning to make decisions in dynamic environments: Effects of time constraints and cognitive abilities. *Human Factors, 46*(3), 449–460.

Gonzalez, C. (2005). Decision support for real-time dynamic decision making tasks. *Organizational Behavior and Human Decision Processes, 96*(2), 142–154.

Gonzalez, C., Lerch, F. J., & Lebiere, C. (2003). Instance-based learning in dynamic decision making. *Cognitive Science, 27*(4), 591–635.

Heath, C., Larrick, R. P., & Klayman, J. (1998). Cognitive repairs: How organizational practices can compensate for individual shortcomings. In B. M. Staw & L. L. Cummings (Eds.), *Research in organizational behavior* (Vol. 20, pp. 1–37). Greenwich, CT: JAI Press.

Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P., Dai, X., Maskell, K., and Johnson, C., eds, (2001). *Climate Change 2001: The Scientific Basis.* Cambridge, UK: Cambridge Univ. Press.

Kahneman, D., & Tversky, A. (1972). Subjective probability: A judgment of representativeness. *Cognitive Psychology, 3*(3), 430–454.

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica, 47*(2), 263–291.

Kaplan, C. A., & Simon, H. A. (1990). In search of insight. *Cognitive Psychology, 22*(3), 374–419.

Klein, W. M. P. (1999). Justifying optimistic predictions with minimally diagnostic information under conditions of outcome dependency. *Basic and Applied Social Psychology, 21*(3), 177–188.

Kleinmuntz, D. N. (1985). Cognitive heuristics and feedback in a dynamic decision environment. *Management Science, 31*(6), 680–702.

Kleinmuntz, D. N., & Schkade, D. A. (1993). Information displays and decision processes. *Psychological Science, 4*(4), 221–227.

Kotovsky, K., Hayes, J. R., & Simon, H. A. (1985). Why are some problems hard? Evidence from Tower of Hanoi. *Cognitive Psychology, 17*(2), 248–294.

Legrenzi, P., Girotto, V., & Johnson-Laird, P. N. (1993). Focussing in reasoning and decision making. *Cognition, 49*(1–2), 37–66.

Mayer, R. E. (1995). The search for insight: Grappling with Gestalt psychology's unanswered questions. In R. E. Sternberg & J. E. Davidson (Eds.), *The Nature of Insight* (pp. 3–32). Cambridge: MIT Press.

Omodei, M. M., & Wearing, A. J. (1995). The fire chief microworld generating program: An illustration of computer-simulated microworlds as an experimental paradigm for studying complex decision-making behavior. *Behavior Research Methods, Instruments, and Computers, 27,* 303–316.

Paich, M., & Sterman, J. D. (1993). Boom, bust, and failures to learn in experimental markets. *Management Science, 39*(12), 1439–1458.

Paulos, J. A. (1988). *Innumeracy: Mathematical illiteracy and its consequences.* New York: Hill and Wang.

Petty, R. E., & Caccioppo, J. T. (1986). The elaboration likelihood model of persuasion. In *Advances in Experimental Social Psychology* (Vol. 19, pp. 123–205). New York: Academic Press.

Petty, R. E., & Wegener, D. T. (1998). Attitude change: multiple roles for persuasion variables. In D. T. Gilbert, S. T. Fiske, & G. Lindzey (Eds.), *The handbook of social psychology* (4th ed., pp. 323–390). Boston: McGraw-Hill.

Reber, A. S. (1976). Implicit learning of synthetic languages: The role of instructional set. *Journal of Experimental Psychology: Human Learning and Memory, 2*(1), 88–94.

Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General, 118*(3), 219–235.

Rettinger, D. A., & Hastie, R. (2001). Content effects on decision making. *Organizational Behavior and Human Decision Processes, 85*(2), 336–359.

Ross, W. T., & Creyer, E. H. (1992). Making inferences about missing information: The effects of existing information. *Journal of Consumer Research, 19*(1), 14–25.

Simon, H. A. (1979). *Models of thought.* New Haven, CT: Yale University Press.

Simon, H. A. (1991). Bounded rationality and organizational learning. *Organization Science, 2*(1), 125–134.

Sterman, J. D. (1989a). Misperceptions of feedback in dynamic decision making. *Organizational Behavior and Human Decision Processes, 43*(3), 301–335.

Sterman, J. D. (1989b). Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science, 35*(3), 321–339.

Sterman, J. D. (2002). All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review, 18*(4), 501–531.

Sterman, J. D., & Booth Sweeney, L. (2002). Cloudy skies: Assessing public understanding of global warning. *System Dynamics Review, 18*(2), 207–240.

Sterman, J. D. & Booth Sweeney, L. (2006). Understanding Public Complacency About Climate Change: Adults' mental models of climate change violate conservation of matter. forthcoming, *Climatic Change.* Available at web.mit.edu/jsterman/www/Understanding_public.html.

Tversky, A., & Kahneman, D. (1986). Rational choice and the framing of decisions. *Journal of Business, 59*(4), S251–S278.

Table 1. Results of the Baseline Department Store Task

Rows show number *N* (top panel) and percent (bottom panel) answering each question in Figure 1 with the time specified in the first column (±1 minute to account for possible participant error in reading time-axis values). For example, 166 selected t = 3, 4, or 5 minutes to answer "During which minute did the most people enter the store?" (the correct answer is 4). Probabilities report the Fisher exact test of the null hypothesis that the proportions answering correctly are equal for the two question order treatments O1 and O2 (see text). Bold entries highlight correct responses. Italics show those incorrectly specifying the maximum net inflow/net outflow instead of maximum/minimum in the store.

N	Most Entering?			Most Leaving?			Most in Store?			Fewest in Store?		
	O1	O2	Sum	O1	O2	Sum	O1	O2	Sum	O1	O2	Sum
Max Entering t= 4	**82**	**84**	**166**	0	0	0	2	4	6	1	0	1
Max Leaving t=21	1	1	2	**82**	**82**	**164**	0	1	1	1	2	3
Max in Store t=13	0	0	0	0	0	0	**37**	**39**	**76**	1	3	4
Fewest in Store t=30	0	0	0	0	0	0	0	1	1	**26**	**28**	**54**
Max Net Inflow t= 8	0	4	4	0	0	0	*26*	*24*	*50*	0	0	0
Max Net Outflow t=17	0	0	0	0	6	6	5	1	6	*29*	*22*	*51*
Initial in Store t= 1	0	0	0	0	0	0	0	0	0	5	7	12
Can't be Determined	0	0	0	0	0	0	12	17	29	18	25	43
Other	1	0	1	1	1	2	0	2	2	0	2	2
No Answer	0	0	0	1	0	1	2	0	2	3	0	3
Total	84	89	173	84	89	173	84	89	173	84	89	173
H_0: Correct(Order 1) = Correct(Order 2)? (Fisher Exact Test)	p = 0.44			p = 0.17			p = 1.0			p = 1.0		

%	Most Entering?			Most Leaving?			Most in Store?			Fewest in Store?		
	O1	O2	Sum	O1	O2	Sum	O1	O2	Sum	O1	O2	Sum
Max Entering t= 4	**97.6**	**94.4**	**96.0**	0.0	0.0	0.0	2.4	4.5	3.5	1.2	0.0	0.6
Max Leaving t=21	1.2	1.1	1.2	**97.6**	**92.1**	**94.8**	0.0	1.1	0.6	1.2	2.2	1.7
Max in Store t=13	0.0	0.0	0.0	0.0	0.0	0.0	**44.0**	**43.8**	**43.9**	1.2	3.4	2.3
Fewest in Store t=30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.6	**31.0**	**31.5**	**31.2**
Max Net Inflow t= 8	0.0	4.5	2.3	0.0	0.0	0.0	*31.0*	*27.0*	*28.9*	0.0	0.0	0.0
Max Net Outflow t=17	0.0	0.0	0.0	0.0	6.7	3.5	6.0	1.1	3.5	*34.5*	*24.7*	*29.5*
Initial in Store t= 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	7.9	6.9
Can't be Determined	0.0	0.0	0.0	0.0	0.0	0.0	14.3	19.1	16.8	21.4	28.1	24.9
Other	1.2	0.0	0.6	1.2	1.1	1.2	0.0	2.2	1.2	0.0	2.2	1.2
No Answer	0.0	0.0	0.0	1.2	0.0	0.6	2.4	0.0	1.2	3.6	0.0	1.7

Table 2. Experiment 1: Success Rates Between Visual Isomorphs

		Question 1: Most Entering?	Question 2: Most Leaving?	Question 3: Most in store?	Question 4: Fewest in Store?
	Overall Success Rate (*N* = 264)	89%	83%	56%	46%
A	Graph (both line and bar, *N* = 127)	94%	91%	61%	48%
	No graph (both text and table, *N* = 137)	85%	76%	51%	44%
	Exact test p =	*0.015*	*0.001*	*0.137*	*0.537*
B	Line graph (*N* = 63)	94%	87%	52%	41%
	Bar graph (*N* = 64)	95%	95%	69%	55%
	Exact test p =	*0.718*	*0.127*	*0.071*	*0.157*
C	Text (*N* = 59)	86%	75%	47%	42%
	Table (*N* = 78)	83%	77%	54%	45%
	Exact test p =	*0.811*	*0.841*	*0.493*	*0.862*
D	Baseline (*N* = 173)	96%	95%	44%	31%
	Line graph (*N* = 63)	94%	87%	52%	41%
	Exact test p =	*0.490*	*0.083*	*0.302*	*0.166*

Table 3. Experiment 2: Success Rates Across Cover Stories

	Overall success rates (*N* = 47)	Question 1: Most Entering?	Question 2: Most Leaving?	Question 3: Most in Store?	Question 4: Fewest in Store?
		96%	**94%**	**28%**	**26%**
A	Store (*N* = 18)	100%	100%	22%	17%
	Cars (*N* = 16)	100%	100%	38%	31%
	Exact test p =	*1.000*	*1.000*	*.457*	*.429*
B	Store (*N* = 18)	100%	100%	22%	17%
	Tub (*N* = 13)	85%	77%	23%	31%
	Exact test p =	*.168*	*.064*	*1.000*	*.413*
C	Tub + cars (*N* = 29)	93%	90%	31%	31%
	Store (*N* = 18)	100%	100%	22%	17%
	Exact test p =	*.517*	*.276*	*.739*	*.324*
D	Tub (*N* = 13)	85%	77%	23%	31%
	Cars (*N* = 16)	100%	100%	38%	31%
	Exact test p =	*.192*	*.078*	*.454*	*1.000*

Table 4A. Experiment 3: Effect of Motivation and Feedback on Success Rates for Task 1

	Question 1: Most Entering?	Question 2: Most Leaving?	Question 3: Most in store?	Question 4: Fewest in Store?
No motivation/no feedback condition (*n* = 37)	100%	86.5%	18.9%	21.6%
Motivation/feedback condition (*n* = 32) Task 1 (Figure 4A): Attempt 1	93.8%	96.9%	15.6%	12.5%
Exact test, *p* =	*.211*	*.205*	*.761*	*.359*
Attempt 2	100%	100%	28.1%	25.0%
Attempt 3			56.3%	50.0%
Attempt 4			65.6%	62.5%
Attempt 5			68.8%	71.9%
Attempt 6			71.9%	81.3%
Attempt 7			81.3%	84.4%
Attempt 8			81.3%	84.4%
Attempt 9			81.3%	84.4%

Table 4B. Experiment 3: Effect of Feedback on Problem Success in the High-Motivation Condition

	Question 3: Most in Store?	**Question 4: Fewest in Store?**
Correct on first try	5 of 32 **(15.6%)**	4 of 32 **(12.5%)**
Correct on second try	4 of 27 **(14.8%)**	4 of 28 **(14.3%)**
Exact test p =	*1.00*	*1.00*

Table 4C. Experiment 3: Effect of Manual Calculation on Success, Task 1 (Figure 4)

	Question 3: Most in Store? (First Try)	Question 4: Fewest in Store? (First Try)	Did Not Finish
Manual calculation ($N = 22$)	14%	9%	23%
No written calculation ($N = 10$)	20%	10%	40%
Exact test p =	*.637*	*1.00*	*.407*

Table 5. Experiment 4: Comparison of Success Rates with Missing Flows

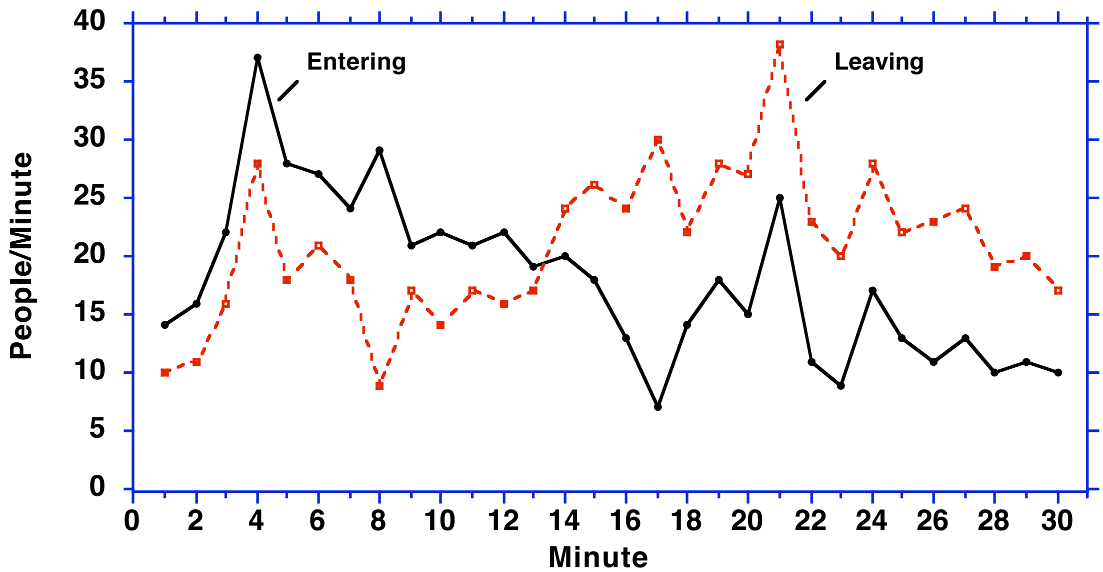
N = 30	Question 1: Most Entering?	Question 2: Most Leaving?	Question 3: Most in Store?	Question 4: Fewest in Store?
Missing stock	90%	79%	3%	10%
Missing outflow	90%	10%	75%	79%
Missing inflow	7%	76%	79%	66%

Table 6. Experiment 5: Influence of Priming on Success

	Question 1: Most Entering?	**Question 2: Most Leaving?**	**Question 3: Most in Store?**	**Question 4: Fewest in Store?**
Baseline (*N* = 37)	95%	92%	8%	16%
Priming condition (*N* = 37)	86%	89%	27%	38%
Exact test p =	*.430*	*.999*	*.063*	*.065*
Prime correct (*N* = 19)	95%	95%	53%	68%
Prime incorrect (*N* = 18)	78%	83%	0%	6%
Exact test p =	*.180*	*.340*	*.0004*	*.0001*

Figure 1. Department Store Task

The graph below shows the number of people *entering* and *leaving* a department store over a 30-minute period.



Please answer the following questions.

Check the box if the answer cannot be determined from the information provided.

1. During which minute did the most people enter the store?

Minute ________ ❑ Can't be determined

2. During which minute did the most people leave the store?

Minute ________ ❑ Can't be determined

3. During which minute were the most people in the store?

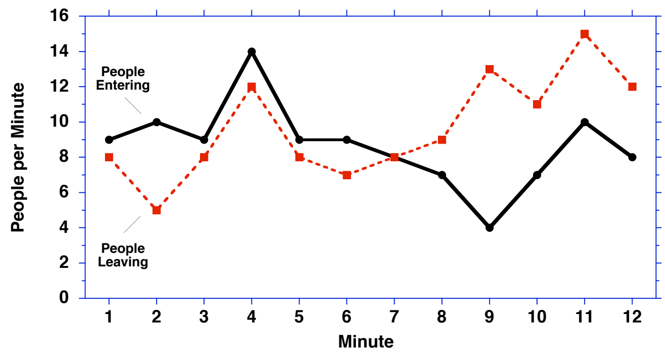
Minute ________ ❑ Can't be determined

4. During which minute were the fewest people in the store?

Minute ________ ❑ Can't be determined

Figure 2. Experiment 1: Visual Isomorphs for the Simpler Department Store Task

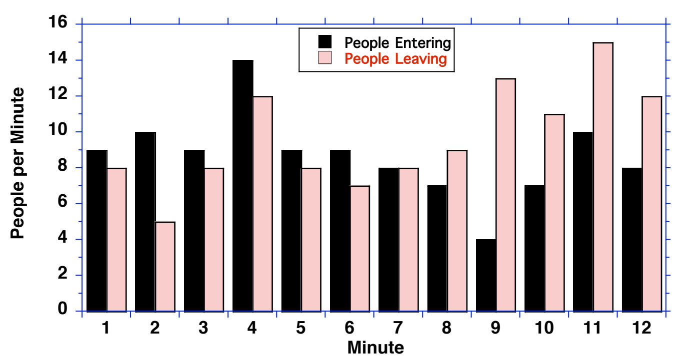
A. Line graph



C. Table

Minute	People Entering	People Leaving
1	9	8
2	10	5
3	9	8
4	14	12
5	9	8
6	9	7
7	8	8
8	7	9
9	4	13
10	7	11
11	10	15
12	8	12

B. Bar Graph



D. Text

In the first minute, 9 people enter and 8 leave. In the second minute, 10 people enter and 5 leave. In the third minute, 9 people enter and 8 leave. In the fourth minute, 14 people enter and 12 leave. In the fifth minute, 9 people enter and 8 leave. In the sixth minute, 9 people enter and 7 leave. In the seventh minute, 8 people enter and 8 leave. In the eighth minute, 7 people enter and 9 leave. In the ninth minute, 4 people enter and 13 leave. In the tenth minute, 7 people enter and 11 leave. In the eleventh minute, 10 people enter and 15 leave. In the twelfth minute, 8 people enter and 12 leave.

Figure 3. Simple Graph Used in Cronin and Gonzalez (in press)

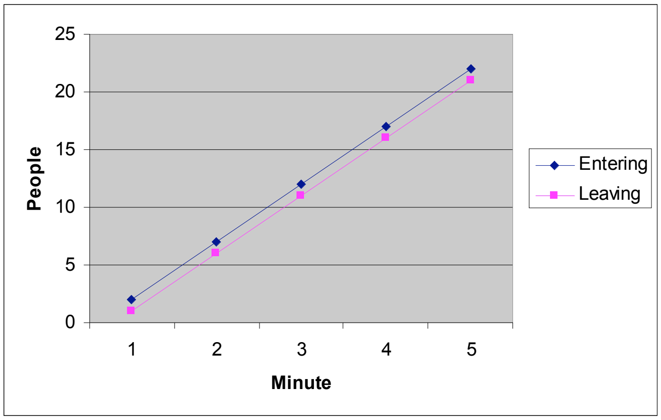


Figure 4. Experiment 2: Graph Used in Motivation Experiments

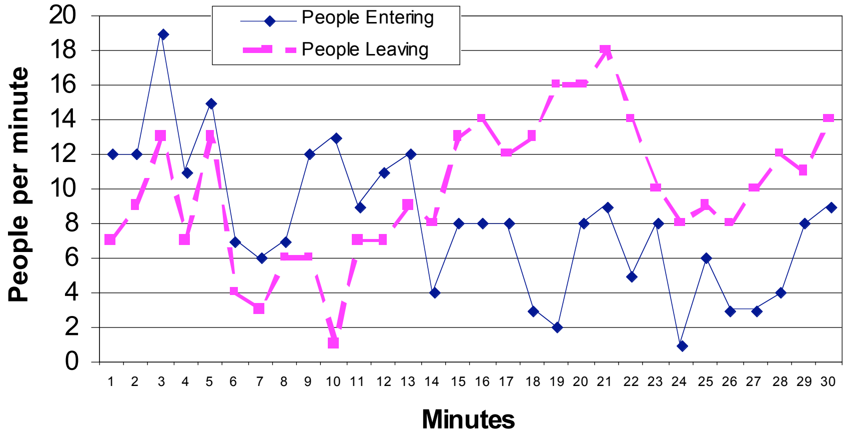
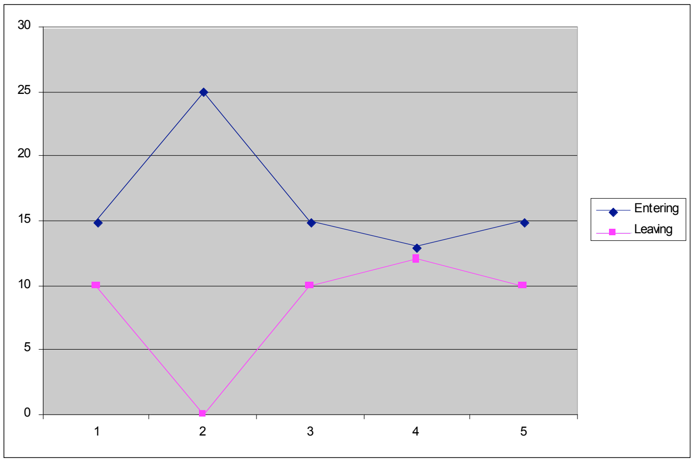
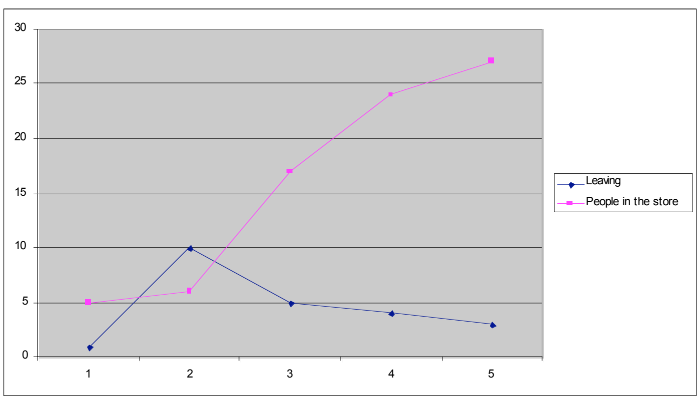


Figure 5. Missing Component Graphs

A. Missing Stock



B. Missing Inflow



C. Missing Outflow

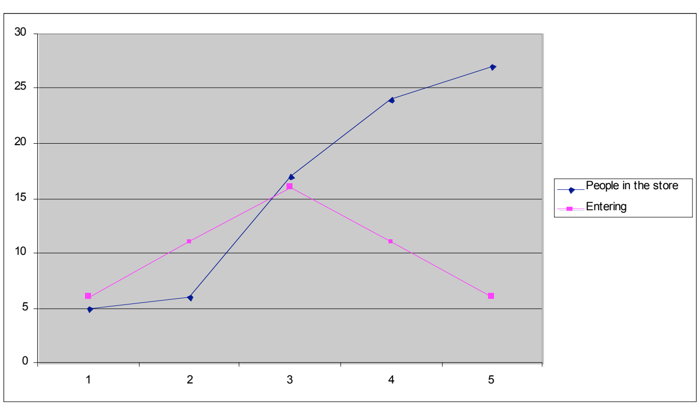
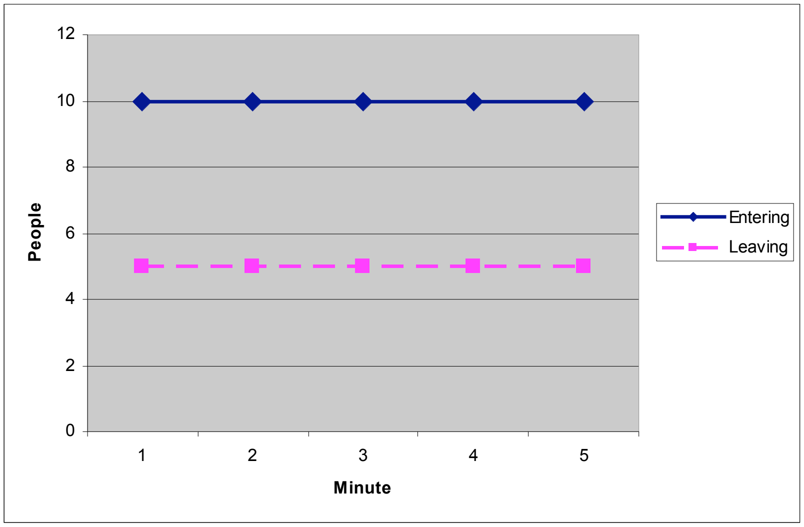


Figure 6. Experiment 5

A. Priming Task



Write down how many people are in the store each minute:

Minute 1:
Minute 2:
Minute 3:
Minute 4:
Minute 5:

B. Simple SF Task (Participants Were Asked the Same Four Questions Shown in Figure 1)