Is Ability of Solving Complex Stock-Flow Problems Associated with Ability of Solving Simpler Ones? An Experiment in Turkey

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ABSTRACT

There are many studies exploring the reasons behind failures in solving generic system dynamics (SD) problems such as stock- flow (SF) failure. Although they reach some limited associations, they do not find any significant cognition related factor explaining the variation in failures except the positive impact of visual saliency of the problem displays. In present study we put forward the question "Does cognitive problem solving capability improves progressively?" So, we prepare a performance sheet including two parts. First part consists of simpler SF problems and second part contains more complex ones. Then we ask these problems to motivated undergraduate industrial engineering students. Sample of participants consists of two groups. First group is SD educated and second group is not SD educated. We see that while some individuals are performing well in solving more complex SD problems, others are performing well in simpler ones, and ability to solve more complex problems is not dependent on performance in solving simpler ones. But we find associations between capabilities of solving two different complex SF problems. We also see that SD education increases the capability of solving complex SF problems but does not affect the capability of solving simpler SF problems.

Keywords: *System Dynamics Education, Simplicity, Complexity, Stock-Flow Problems, Industrial Engineering*

1. Introduction

For a quite long time Systems Dynamics (SD) education in current schooling system has been considered as not only a discipline forcing learners to think in systems but also one of the most important remedies in every phase of education of different disciplines to prepare tomorrow's adults for managing highly complex dynamic systems (Roberts, 1978; Forrester, 1990, 1993, 1997; Booth Sweeney and Sterman, 2000; Lane, 2007). Humanity requires understanding and managing these systems for many reasons from making life easier to maintaining species of our planet including itself.

Stocks and flows are principle elements of SD domain. Capability to understand main building blocks of system dynamics and their dynamic interactions is considered as very important aspect for individuals in order to recognize real life complex systems such as relationships between macroeconomic displays, flow of traffic in rush hours, behavior of an epidemic illness (Dörner, 1980; Sterman, 1994; Meadows, 2008) or acquiring the behavior of stocks and flows of resources such as materials, information, money, etc. (Cronin, Gonzales and Sterman, 2009).

Some scholars have scrutinized the SD education in order to measure the success of applications. They have focused on systematic thinking skills, especially establishing cause and effect relationships and concluded that even highly educated individuals had problems in systematic thinking (Cronin, Gonzales and Sterman, 2009). The studies conducted in order to find the reason behind the success or failure in solving some generic system dynamics problems such as stock-flow (SF) problem do not reveal a robust and satisfactory reason.

Basic stock and flow structure consists of three main components; inflow, stock and outflow. The mathematical representation of stock and flow dynamics can be seen in Equation 1. With a fundamental knowledge of calculus it can be seen in the formal form, the resource in the pool (stock level) increases if inflow surpasses outflow over time.

$$Stock_t = \int_{t_0}^{T} (Inflow - Outflow)\, dt + Stock_{t_0} \tag{1}$$

Cronin et al. (2009) suggest that calculus knowledge is not a prerequisite to understand the dynamics of accumulation and give the example of water tube with a flow of water into the tube and a draining of water out of the tube. They claim that in daily life everyone can imagine that water level rises once the inflow exceeds outflow in unit time.

Although stock and flow problems are considered easy ones, experiments show that these problems are not easy to be solved by even highly educated individuals with a solid mathematics background (Booth Sweeney and Sterman, 2000; Sterman and Booth Sweeney, 2002; Cronin and Gonzalez, 2007). In most of the studies almost half of the respondents give wrong answers. Cronin et al. (2009) call this difficulty in solving stock-flow problems as stock-flow (SF) failure. Several studies have been scrutinized the causes of this cognitive failure.

Booth Sweeney and Sterman (2000) conduct an experiment to students of elite business schools of US to investigate the effect of prior education, age, national origin, etc. on performance of understanding SF relationships. They conclude that there is an overall poorness in performance though the sample has extensive training in mathematics and science. They also report that independent variables which they explore have no significant impact on SF problem solving performance of individuals.

Roch, Lane and Samuelson (2000) investigate the impact of cognitive burden of required calculations on the performance of solving SF problems and find an insignificant association.

Sterman and Booth Sweeney (2002) examine the SF problem performance of students from different distinguished US collages using two tasks such as “zero emission” and “stable CO_2 concentration”. These tasks which are simplified to a level of “require no mathematics” necessitate only understanding of stocks and flows and basic facts about climate change. They find that overall performance of the participants is quite poor. Since they do not understand the dynamic behavior of SF, many of them show a tendency of believing that temperature responds immediately to changes in CO_2 emissions or concentrations, etc. Evidence from their experiment shows that “SF failure” canalizes people to make conclusions violating basic laws of physics.

Atkins, Wood and Rutgers (2002) explore the impact of feedbacks given to participant who are to solve a task dealing with the delay effect in inventory flow and stock. They find that feedback does not improve the performance of participants although they understand the complexity of the problem.

Ossimitz (2002) investigate the impact of “inadequate motivation”, “unfamiliar task context” on the ability to interpret or construct graphs for SF problems using classical department store task. They find that motivation and related context do not significantly influence the performance but there is an unexpected and significant difference between male and female participants’ performance levels.

Cronin and Gonzalez (2007) design an experiment to understand the impacts of motivation level and domain experience on the performance in correctly understanding the dynamic relationship between stock and flows. They find that neither the domain familiarity nor increased motivation helped individuals improve their perception of stock and flow relationships; but their findings show that the graphical representation directs attention to flows and not stocks. They also claim that individuals tend to be appealed by more salient points of a graph rather than comprehending the overall accumulation over time.

Booth Sweeney and Sterman (2007) develop instruments to scrutinize understanding of systems concepts and test them with students and teachers from two middle schools in the USA. Their results indicate that participants perform generally limited intuitive systems thinking abilities with some exceptions. They also report that linear causal thinking is commonplace, logical interpretations lack references to time frame and delays, and age is not a significant factor for SF failure.

Cronin, Gonzales and Sterman (2009) investigate the impact of the education level of individuals on the performance in correctly solving SF problems and on the tendency of correlation heuristic failure. They apply five different experiment settings to see the effects of different variables on the performance of participants. “Cognitive burden and data display”, “task context”, “motivation and feedback”, “priming stock knowledge” and “the difficulty of SD problems” are the issues donated the independent variables of each experiment setting. They cannot find any robust variable which have impact on the performance except “the difficulty of the problems” variable. This variable shows a significant impact on individuals’ failure tendency. As conclusion they claim that well educated individuals from different populations do not show a significant performance especially on the problems asking the stock level at a determined point in time.

Brunstein, Gonzalez and Kanter (2010) explore the effect of domain experience on the performance of SF problem solving. They report that domain experience is not a strong indicator for overcoming the SF failure.

Davidsen, Moxnes, Sánchez and Wheat (2011) investigate water free outflow dynamics ability of students with SD training and trace the effect of overconfident linear thinking intentions in the failures caused by not determining the effect of gravity on the water flow rate.

Martinez-Moyano and Gonzales (2011) approach to problem from visual perception side and investigate the effect of visual saliency on a stock-flow problem performance and find a significant positive association recently.

Almost all of the studies in the literature scrutinize the reason behind SF failure. In this paper, we decided to explore this phenomenon from another perspective and try to categorize subjects in terms of their ability to solve several SF tasks from various complexity levels. In order to extend our knowledge on SF failure we investigate the association between individual's performance in solving simpler SF problems and in solving complex ones. Here we aim to scrutinize whether capability of solving complex SF problems depends on ability to solve simpler ones. We also try to explore the effect of SD education on performance of solving both complex and simpler SD problems.

3. Hypotheses

In order to investigate the association between simpler and complex SF problem solving capabilities and the effect of SD education on both solving capabilities, we propose the hypotheses below.

H_1: Capability of solving simpler SF problem is associated with SD education.
H_2: Capability of solving complex SF problem is associated with SD education.
H_3: Capability of solving simpler SF problems is associated with the capability of solving complex SF problems.

We employ seven stock-flow problems. First three have only an inflow for investigating the capability of predicting the dynamic behavior of stock according to dynamic behavior of inflow. They are arranged from simpler to more complicated. Basically, these problems resemble the bathtub problems used in the literature. Last four problems are innate problems of classical department store task. In this group, first two problems are considered as relatively simpler than the last two. Here we try to understand whether the capability of solving easier SD problems has an impact on the capability of solving more complicated ones.

4. Methodology

4.1. Participants

The sample of the research is comprised of two groups which are randomly chosen from the population of industrial engineering undergraduate students in Istanbul and Ankara/Turkey. First group is SD educated (n=114) via an introductory SD course and second group is not SD educated (n=42). Total number of both groups is 156. The age range of the participants is 20-24 years. The SD educated group having taken an introductory System Dynamics course from three different instructors in three different universities is given the survey instruments as small tests for grading the course. The other group without SD education from two different universities is given the survey instruments as small tests for grading an introductory ergonomics course. Thus, the motivation of the students towards survey instrument is secured. They are given 15 minutes to complete the survey instrument.

4.2. Task

In order to investigate the dynamics of problem solving we employ two groups of problems. For the first group we prepare three basic one flow (inflow) and stock dynamics problems. We give the graphics showing the behavior of flow and accordingly ask participants to draw the dynamic behavior of stock approximately. The problems and their correct answers are indicated in Figure 1.

We also employ the first two problems of classical department store problem which is developed by Sterman (2002) in the simpler group. Last two problems of classical department store problem are employed to construct more complicated problems group.

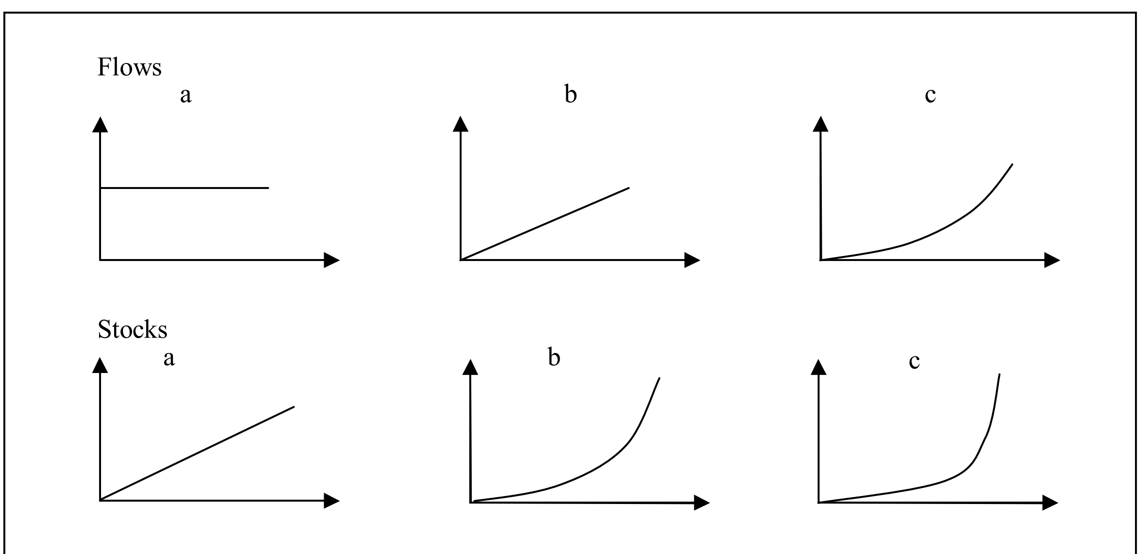


Figure 1. The graphics showing three of the simpler problems of survey instrument and their respective correct answers

We use standard department store task developed by Sterman (2002) to measure the SF problems scores of participants. This task consists of a graph (Figure 2) showing the rate at which people enters and leaves a department store and accordingly four problems to be asked. The first two problems, which are accepted as relatively easier, test individual's performance in determining the difference between lines indicating the number entering and leaving the store in time section. The last two problems, which are accepted as relatively more complex, test their understanding of cumulative level of customer numbers caused by inflows and outflows in time. The minute at which the highest number of customers is reached in the store is the point where the two curves cross. The minute at which the minimum number of customers is observed is the latest, namely the 30th minute.

The first two problems of this task aims to measure the ability to calculate the flow in a determined point in time. The last two problems are for measuring the ability to calculate the stock in determined point in time.

We named five problems as basic or somewhat easy (S1-1, S1-2, S1-3, S2-1 and S2-2) and two problems as more complex (C2-3 and C2-4). So the hypotheses we proposed before are extended as follows.

H_1: Simpler SF problem solving capability is associated with SD education.

H_{1a}: Capability of solving problem S1-1 is sensitive to SD education.

H_{1b}: Capability of solving problem S1-2 is sensitive to SD education.

H_{1c}: Capability of solving problem S1-3 is sensitive to SD education.

H_{1d}: Capability of solving problem S2-1 is sensitive to SD education.

H_{1e}: Capability of solving problem S2-2 is sensitive to SD education.

H_2: Capability of solving complex SF problem solving is associated with SD education.

H_{2a}: Capability of solving problem C2-3 is sensitive to SD education.

H_{2b}: Capability of solving problem C2-4 is sensitive to SD education.

H_3: Capability of solving simpler SF problems is associated with the capability of solving complex SF problems.

H_{3a}: Capability of solving problem S1-1 is associated with solving problem C2-3.

H_{3b}: Capability of solving problem S1-1 is associated with solving problem C2-4.

H_{3c}: Capability of solving problem S1-2 is associated with solving problem C2-3.

H_{3d}: Capability of solving problem S1-2 is associated with solving problem C2-4.

H_{3e}: Capability of solving problem S1-3 is associated with solving problem C2-3.

H_{3f}: Capability of solving problem S1-3 is associated with solving problem C2-4.

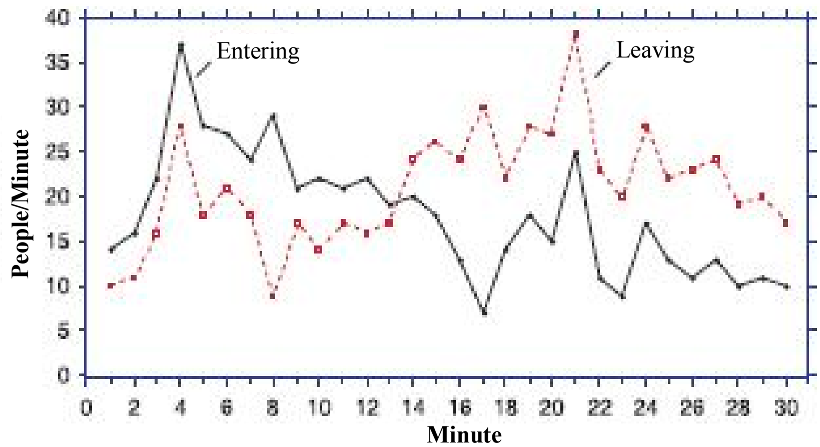
H_{3g}: Capability of solving problem S2-1 is associated with solving problem C2-3.

H_{3h}: Capability of solving problem S2-1 is associated with solving problem C2-4.

H_{3i}: Capability of solving problem S2-2 is associated with solving problem C2-3.

H_{3j}: Capability of solving problem S2-2 is associated with solving problem C2-4.

The graph below shows the number of people **entering** and **leaving** a department store over a 30 minutes 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. Classical Department Store Task (Sterman, 2002)

4.3. Procedure

We employ ANOVA to explore the individual effects of independent variables on each dependent variable. The nature of our experiment is in accordance with the 2^k factorial design which is demonstrated in detail by Montgomery (2001: 218). Since it has seven variables and all variables have two levels which donate a success (1) and a failure (0).

Factorial design has some assumptions; the factors should be fixed, the designs should be completely randomized and the usual normality should be satisfied. In this study, we test all these assumptions and the test results provide that all assumptions are fulfilled (Montgomery, 2001: 170, 218).

5. Results

Table 1 shows the performance of two groups in solving these problems. It can be seen that the success rates of the problems which are denoted as easier are significantly higher than the ones denoted as more complex. The figures here support our effort of classifying the problems of our survey. Similar classification effort concerning the difficulty level of SD problems is deployed in the study of Cronin, Gonzales and Sterman (2009).

Table 1. Descriptive Results Showing the Performance of Two Groups of Participants

	Total		**S1-1**		**S1-2**		**S1-3**		**S2-1**		**S2-2**		**C2-3**		**C2-4**	
	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
SD Educated	114	73	102	89	82	72	95	83	108	95	105	92	38	33	26	23
Non-SD Educated	42	27	35	83	25	60	25	60	41	98	39	93	5	12	3	7
Total	156	100	137	88	107	69	120	77	149	96	144	92	43	28	29	19

In Table 1 we put performance frequencies concerning correct responses of participants to simpler and complex problems concerning their SD education background.

As it can be seen in Table 2 the performance of individuals in any simpler problems has no significant association with their performance in solving complex problems. We find that capabilities of correctly solving complex problems are related with each other significantly.

Table 2. ANOVA Tests Results

Dependent Variable:C2-3					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	12,620[a]	6	2,103	16,915	0,000
Intercept	3,868	1	3,868	31,107	0,000
S1-1	0,089	1	0,089	0,716	0,399
S1-2	0,232	1	0,232	1,863	0,174
S1-3	0,072	1	0,072	0,580	0,447
S2-1	0,020	1	0,020	0,164	0,686
S2-2	0,001	1	0,001	0,006	0,938
C2-4	**11,470**	**1**	**11,470**	**92,246**	**0,000**
Error	18,527	149	0,124		
Total	43,000	156			
Corrected Total	31,147	155			
R Squared = ,405 (Adjusted R Squared = ,381)					
Dependent Variable:C2-4					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	9,686[a]	6	1,614	17,276	0,000
Intercept	1,608	1	1,608	17,207	0,000
S1-1	0,211	1	0,211	2,260	0,135
S1-2	0,006	1	0,006	0,066	0,798
S1-3	0,026	1	0,026	0,283	0,596
S2-1	0,131	1	0,131	1,399	0,239
S2-2	0,099	1	0,099	1,055	0,306
C2-3	**8,620**	**1**	**8,620**	**92,246**	**0,000**
Error	13,923	149	0,093		
Total	29,000	156			
Corrected Total	23,609	155			
R Squared = ,410 (Adjusted R Squared = ,387)					

The impacts of variables representing simpler problem solving capability (S1-1, S1-2, S1-2, S1-3, S2-1, S2-2) are not significant at α= 0.05 level. Merely the variables representing more complicated problem solving capability (C2-3, C2-4) are significant at α= 0.05 level for each other. It means that performance of individuals in solving more complicated problems is not affected by their performance in simpler ones.

In order to see the impact of SD education on each of the problems we employ multiple ANOVA analysis. As it can be seen on Table 3, SD education has a positive and significant impact only on S1-3 and complex problems (C2-3and C2-4). S1-3 is the only problem among simpler ones questioning the ability of constructing stock behavior fed by a nonlinear flow. So, predicting the association between nonlinear flow and stock can naturally be influenced by SD education.

Table 3. ANOVA Tests Results Showing the Effect of SD Education

Dependent Variable		Type III Sum of Squares	df	Mean Square	F	Sig.
SD Education	S1-1	,116	1	,116	1,075	,301
	S1-2	,472	1	,472	2,195	,140
	S1-3	1,740	1	1,740	10,325	**,002**
	S2-1	,025	1	,025	,590	,444
	S2-2	,002	1	,002	,024	,877
	C2-3	1,409	1	1,409	7,298	**,008**
	C2-4	,753	1	,753	5,074	**,026**

The results of the proposed hypotheses are presented in Table 4. The effect of SD education on the capability of solving simpler SF problems is not supported in terms of hypotheses H_{1a} and H_{1b}. But in terms of H_{1c} the capability of solving S1-3 problem is found to be associated positively and significantly with SD education. The hypotheses (H_{2a} and H_{2b}) investigating the association between SD education and complex SF problem solving capability is supported. The hypothesis ($H_{3a\text{-}f}$) concerning the association between simpler SF problem solving capability and complex SF problem solving capability are not supported.

Table 4. Results of Hypotheses Tested

#	**Hypotheses**	**Results**
H_{1a}	Capability of solving problem S1-1 is sensitive to SD education.	Not supported
H_{1b}	Capability of solving problem S1-2 is sensitive to SD education.	Not supported
H_{1c}	Capability of solving problem S1-3 is sensitive to SD education.	Supported
H_{1d}	Capability of solving problem S2-1 is sensitive to SD education.	Not supported
H_{1e}	Capability of solving problem S2-2 is sensitive to SD education.	Not supported
H_{2a}	Capability of solving problem C2-3 is sensitive to SD education.	Supported
H_{2b}	Capability of solving problem C2-4 is sensitive to SD education.	Supported
H_{3a}	Capability of solving problem S1-1 is associated with solving problem C2-3	Not supported
H_{3b}	Capability of solving problem S1-1 is associated with solving problem C2-4.	Not supported
H_{3c}	Capability of solving problem S1-2 is associated with solving problem C2-3.	Not supported
H_{3d}	Capability of solving problem S1-2 is associated with solving problem C2-4.	Not supported
H_{3e}	Capability of solving problem S1-3 is associated with solving problem C2-3.	Not supported
H_{3f}	Capability of solving problem S1-3 is associated with solving problem C2-4	Not supported
H_{3g}	Capability of solving problem S2-1 is associated with solving problem C2-3	Not supported
H_{3h}	Capability of solving problem S2-1 is associated with solving problem C2-4.	Not supported
H_{3i}	Capability of solving problem S2-2 is associated with solving problem C2-3.	Not supported
H_{3j}	Capability of solving problem S2-2 is associated with solving problem C2-4.	Not supported

6. Discussion and Conclusion

Some scholars claim that although infants are naturally born systems thinkers, they are losing their ability to think in systems by means of suppressing schooling environment making them to get universe fragmented and consist of unrelated parts, while their perception of understanding complexity increases (Booth Sweeney and

Sterman, 2000). But system dynamics education can be an instrument to increase the ability of thinking in systems. Although Davidsen, et al. (2011) claim SD education does not affect the performance of students in solving dynamic problems, we found that complex problems questioning the ability to predict stock level which is caused by both inflow and outflow in a determined point in time, is influenced by SD education. On the other hand we find no evidence of SD education impact on simpler problems questioning the ability of predicting the stock level caused by only inflow and the flow amount in a point in time frame. But we trace an association between SD education and capability of predicting stock behavior caused by an exponentially increasing flow. We think that nonlinearity in the nature of this problem may make participants' performance sensitive to SD education.

In this paper we aim to explore the association between capability of solving simpler and complex problems concerning the dynamic behaviors. After the experiment and analyses, the hypothesis we proposed are tested. The theory of progressive increase of individuals' performance in solving SF problems has been failed. In other words, individuals who can correctly answer complex problems are mostly not the ones who answer the simpler problems correctly. In daily life we see some students who can easily solve complex tasks but fail to solve simpler ones in science and mathematics courses. Many scholars interpret this failure as lack of attention. Moreover, parents caution their children to be more careful about these simpler problems in their exams.

The results here force us to move beyond the traditional views of cognition theories as there is a different thinking ability among the all (at least the participants of this experiment). They provide a much broader understanding of complex relations in stock and flow problems. Within this framework we sense some possibilities of redefining the thinking capacity as "complex thinking" and "simple thinking". Complex thinkers are different than simple thinkers in many ways. They are able to solve complex problems, see complex relations, and comprehend complex structures though they are insufficient in simple ones. However, some components of this framework still remain to be addressed. For example, it will be important to examine the level of concentration of the participants. It may be expected that it should be higher in complex problems than the simple ones. But even if this claim is accepted as effective, the reasons of decreased level of concentration should be questioned. It will also be important to test other groups (preschools and K-12 for example) if this difference in thinking is innate or somehow a side effect of education system. A further question regards the role of culture on thinking abilities; if it is a cultural dependency of seeing only one side of the problems. These studies may shed light on how and why some are bad in solving simple problems while they are well in complex ones. To conclude, we discuss the implications of our theory for existing and future research.

Researchers interested in further considering SF problems should deal with two issues in particular. First, individuals may differ in terms of how aware they are of the structure of the problem. We would expect further researchers to investigate the reason behind this phenomenon is whether the structure of the problem or the innate features of individuals. Second, we suggest researchers consider how personality type, culture, and education level impacts our theoretical propositions.

Dispersion in SF problems is not simply a practical success concern of any training methodology for researchers. Instead, it is a worthwhile theoretical challenge of research. We as scholars need to move beyond basic assumptions and conceptualize the approach for complexity of its theory. This theory offers researchers a framework for examining the impact of success on solving complex problems. We invite other scholars to extend this theory and begin developing an empirical base of research that tests our theory.

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