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Learning Design Framework for Constructive Strategic Alignment with Visualizations

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Abstract: Prior research on integrating computer-based visualization tool in teaching has shown that the use of constructivist strategies has led to positive learning outcome. Yet multiple surveys report that instructors face difficulty in integrating visualizations in their teaching. A probable cause is that instructors, on their own, are unable to achieve effective alignment between the instructional strategy used with visualization and their instructional objective. Currently no guidelines exist for instructors for attaining such alignment while teaching with technological tools like visualizations. To address this problem, we propose the Customized Visualization Integration (CVI) framework based on outcomes-based teaching approach that targets 'constructive strategic alignment' i.e. alignment between student-centered instructional strategies and instructional objectives with the visualization. CVI provides instructors with 'easy-to-use' guidelines that can be combined to create learning designs (LDs) customized to their set of instructional objectives with visualization. Furthermore, it provides LDs customized to individual objectives based on these guidelines. In current paper, we also present empirical validation for a subset of the proposed guidelines through a field experiment with 144 engineering under-graduates.

Keywords: Framework, visualization, constructive strategic alignment, learning design.

1. Introduction

Computer-based visualizations involve "the use of computer supported, interactive, visual representations of data to amplify cognition" (Tory & Moller, 2004) like educational animations and simulations. These visualizations improve conceptual and procedural understanding and develop reasoning and prediction skills (Rutten et.al, 2012). However, their learning effectiveness is dependent on the instructional method used (Bratina et.al, 2002). Empirical studies show that use of constructivist strategies with visualizations like think-pair-share (McConnell, 1996) leads to improved learning outcome. Another important criterion is alignment between the strategy used and the instructional objectives (Boyle, 2012). There are several studies (Biggs, 1999; Cohen, 1987) emphasizing the importance of strategic alignment in teaching. Cohen (1987) cites multiple empirical studies that show significantly reduced learning outcome due to non-alignment between instructional strategy and objective. Thus, effective integration of visualization in teaching entails use of constructivist strategies aligned with the instructional objective i.e. constructive strategic alignment. But multiple surveys (Shaffer et.al, 2011) reveal that instructors face difficulty in integrating visualizations in their teaching. This difficulty occurs along two fronts – designing for constructive strategic alignment on their own (Conole et.al, 2004) and ensuring implementation fidelity for constructivist strategies (Ebert-May et.al, 2011). The existing solutions like learning designs (LDs) and learning taxonomies do not provide instructors with detailed guidelines on how to achieve this alignment with visualization. In fact, there is no prior study identifying instructional objectives with visualizations. Thus, a learning design framework with 'easy-to-use' guidelines for instructors to achieve strategic alignment for different objectives with visualization is needed. CVI (Customized Visualization Integration) is such a learning design framework that provides instructors with guidelines and LDs to achieve strategic alignment with visualization. The contribution of this paper is the CVI framework and its three major components - i) Instructional objectives with visualization identified through an exploratory study with Science and Engineering instructors, ii) 'Easy-to-use' guidelines that instructors can use to create LDs aligned to objectives. iii) LDs mapped to individual objectives with visualization. We also validate the guidelines for four types of objectives with visualization, encompassing problem-solving and conceptual understanding through a controlled field experiment with 144 Electrical Engineering students.

2. Related Work

Multiple empirical studies report the benefits of using constructivist strategies with visualizations like think-pair-share (McConnell, 1996) across different instructional settings like lecture, laboratory and self-learning. But, instructors face problems in attaining constructive alignment with visualizations and maintaining implementation fidelity for the constructivist strategies. In this section we discuss a subset of learning taxonomies like Bloom's, SOLO taxonomy, Component Display Theory and Morrison's Extended Content Performance matrix among the many that exist. These taxonomies do not address strategic alignment for teaching with a technological tool like visualization. For example, Revised Bloom's taxonomy provides six cognitive levels of learning objectives to guide alignment between strategy and objective. In the 'Component Display Theory'(Merrill, 1983) instructors can choose strategy for a complete lesson based on three major factors – i) content type (Facts, Concepts, Procedures, Principles) and performance objectives expected from students (Remember, Use, Find) ii) type of primary and associated secondary presentation forms and iii) rules relating presentation forms to content performance matrix. Morrison et. al. (2010) also bases their work on a content-performance matrix where performance objective is restricted to Recall and Application and instructional strategies to four categories – Elaboration, Organizational, Integrative and Recall. However, none of these focus on teaching with visualization nor do they provide detailed implementation plan to instructors. The other problem of implementation fidelity refers to how well the strategy execution follows the defined procedure. Empirical studies (Ebert-May et.al, 2011) have found that majority of the faculty, who professed using constructivist strategies, in fact veered towards teacher-centered teaching in their lectures. To address this problem, learning designs (LDs) provide stepwise implementation plan to instructors. They help instructors execute pedagogically sound instructional activities mapped for different types of media and instructional setting (Mor & Brock, 2012). But they do not map instructional activities to specific instructional objectives with visualization. Thus, no guidelines currently exist for instructors on achieving constructive strategic alignment with visualization.

3. Solution Approach & Research Questions

The objective of the current study was to build the CVI framework to assist instructors in effectively integrating visualizations in their teaching**.** This framework takes as its input the instructor's choice of instructional objectives with visualization. It then identifies instructional strategy design components aligned to the chosen objectives. The term 'instructional strategy design components' refers to functional units within the strategy like raising cognitive conflict or students verbalizing their problem solving strategy. CVI outputs guidelines to achieve strategic with visualization as also LDs, mapped to particular objectives that specify stepwise execution plan to achieve the alignment.

The three research questions explored in the study were:

- RQ1: What categories of instructional objectives do instructors have while teaching with visualization? (Section 4.1)
- RQ2: What are the instructional strategy design components necessary to achieve alignment with each of the identified objectives with visualization? (Section 4.2)
- RQ3: What is the ecological validity of the mapping proposed by CVI framework between instructional objectives with visualization and instruction strategy used, for a chosen subset of objectives? (Section 5)

4. Formulating CVI (Customized Visualization Integration) Framework

The CVI framework was built in two consecutive phases with each phase having its own separate methodology. In phase 1, we identified instructional objectives with visualization through an exploratory study of semi-structured instructor interviews. In phase 2, we mapped these objectives with instructional strategy design components through analysis and synthesis of literature.

4.1 Identifying Instructional Objectives with visualization

We did a qualitative study by conducting semi-structured interviews with 61 instructors from multiple domains of science and engineering like Chemistry, Physics, Computer Science, Electrical. The instructors had teaching experience of 5-20 years and had used visualization in teaching. During the interviews, which ranged from 50-60 minutes, instructors were asked to show sample visualizations they had used and what their instructional objective was with that visualization. The interview responses were coded by two researchers through the open and axial coding stages (Corbin & Strauss, 2008) with an inter-rater agreement of unweighted Kappa 0.81. The interviews were interleaved with the open coding phase. Hence, questions asked in subsequent interviews were influenced by the open codes emerging from analysis of previous interviews. The open codes thus obtained for all the interviews were grouped into broader categories in the axial coding phase (Table 1). A total of 11 objective categories emerged which were of finer granularity than those proposed in existing learning taxonomies. In this paper we report a subset of four such objectives that were part of our validation experiment (Table 4).

Table 1: Sample coding of instructional objectives with visualization.

Interview response (verbatim)	Open Code	Axial Code
Observe the phenomenon & construct an explanation of conductor properties & fields	Frame the definition of a concept after observing the visualization	Derive, through logical reasoning, definition of a concept/relationship between variables or algorithm of a process from observations made from the visualization
Observe the visualization on sorted linked list & write a simple algorithm for it	Develop the logic of process execution with given input parameters & specified output, after observing visual demonstration of the process	
Observe the Brayton cycle visualization & draw the temperature-entropy diagram	Predict relationship between different variables while watching the visualization, before the concept is taught	

4.2 Identifying Instructional Strategy Design Components

In phase 2, the instructional objectives obtained were analyzed for their cognitive rigor and specific skills targeted, if any, like multiple representation or problem solving. We determined the cognitive rigor from the Cognitive Rigor (CR) matrix (Hess et.al, 2009) comprising of Bloom's cognitive level and Webb's depth of knowledge. We then analyzed and synthesized relevant literature to identify instructional strategy design components mapped to the objective categories. For example, for the objective of 'Write/Draw alternate representations from the given visualization or vice-versa.', we analyzed literature on teaching and learning of multiple representations as well as application of conceptual knowledge to identify design components relevant for the objective (Table 2). Based on this mapping, we framed guidelines for instructors on what design components to include in their learning designs to achieve strategic alignment (Table 2). We also created sample learning designs (LDs), mapped to individual objectives, that give stepwise implementation plan for attaining constructive strategic alignment (Fig. 1). We found the required design components for a particular objective can be operationalized through multiple constructivist strategies. Hence, CVI has taken a sample set of constructivist strategies like TPS-V (Think-Pair-Share with Visualization) to illustrate the execution of the recommended mappings (Fig. 1).

Table 2: Sample Instructional Strategy Design Components mapped to objectives with visualization.

Instructional Objective with Visualization	Necessary Instructional Strategy Design Components	Guidelines for strategic alignment
Write/Draw alternate representations from the given representation in the visualization or vice-versa.	i) 'Dynamically link the multiple representations. (Der Meij & De Jong, 2006) ii) Make students actively integrate visualizations themselves (Ainsworth, 2006) iii) Show integration of representations (Ainsworth, 2006)	Design a group activity where the instructor will: i) Give a focus question, for each aspect of the information that requires students to vary parameters in one representation and simultaneously reflect on the change in the other representation (for e.g. graph and equation). ii) Follow up with an activity that asks students to integrate all the aspects into a whole (for e.g. for signal transformation, represent each transformation type individually & then integrate) iv) Play the visualization that does all of the above steps to provide feedback.

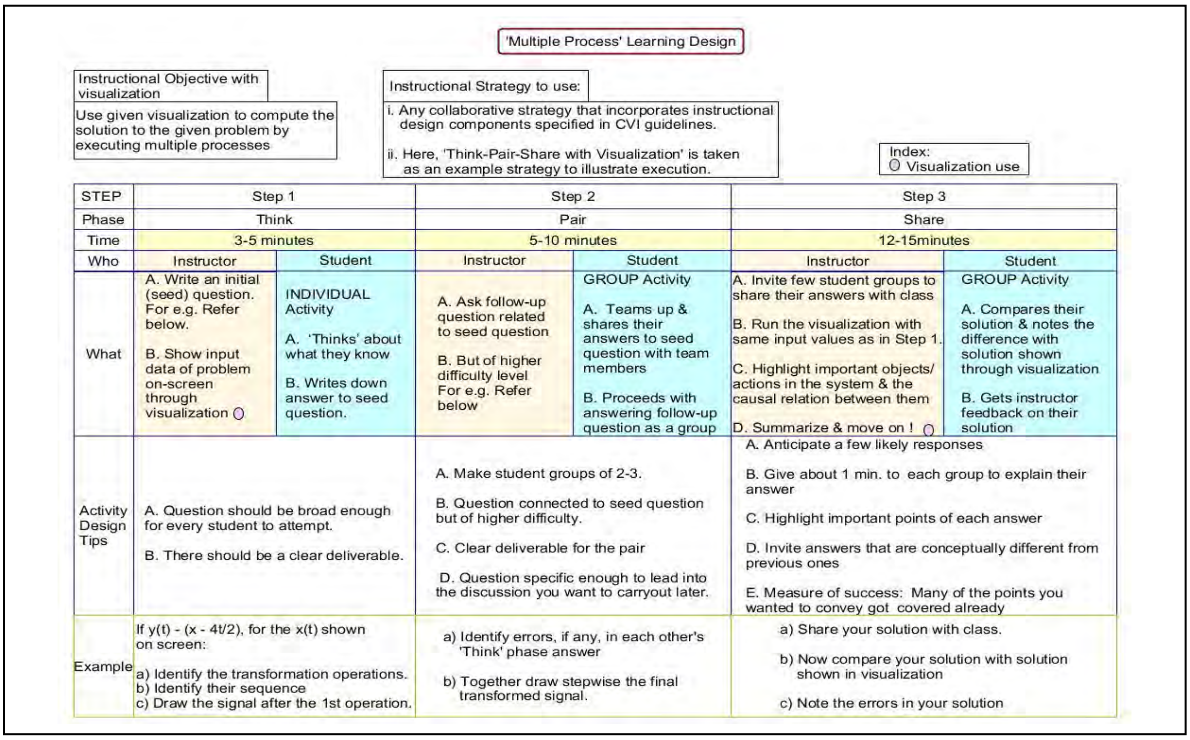

Figure 1: Sample Learning Design mapped to 'Multiple Process' objective

5. Validating CVI Framework

To validate the CVI framework, we conducted a two-group controlled field experiment in a tutorial class on the topic of 'Signal Transformation' in 'Signals and Systems' (Electrical Engineering). The experimental group (N= 70) performed a 30 minute instructional activity designed as per CVI guidelines for four objectives (Table 3) that formed the core of problem solving for the chosen topic. The control group (N= 74) activity was of same duration but was not based on CVI guidelines for three of the objectives (Table 4). The CVI guideline for the fourth objective, involving problem solving with a single process, was the control group activity of watching the visualization with instructor commentary. This guideline was included for validation since we wanted to verify that a non-constructivist activity was sufficient if the objective was at simple recall/reproduction level. Student interaction with visualization for both the groups was mediated through the instructor. After the visualization activity, both groups solved the same post-test questions for 30 minutes. The post-test results of the two groups were compared through non-parametric Mann-Whitney U test since the test scores showed non-normal distribution. The experimental group did statistically significantly better than the control group for the three objectives where CVI guidelines were followed by the experimental group activity (Table 4). For the fourth objective of problem solving with a single process, both groups performed equally well as expected. These results validated the CVI guidelines.

Table 3: Sample of Experimental group activity derived from CVI guidelines.

Instructional Objective with Visualization	Experimental group activity derived from CVI guidelines
Write/Draw alternate representations from the given representation in the visualization or vice-versa.	•Think Phase (5 minutes) [Individual activity] a) Identify what transformation operations are happening in given equation. b) Draw & write down mathematical expression for the first transformation •Pair Phase (10 minutes) [Collaborative activity] a) Discuss and draw stepwise the final transformed signal with the mathematical expression for each step. • Share Phase (15 minutes) [Feedback] a) Compare your answer with the solution shown by the visualization

Table 4: Mann-Whitney U test results for post-test.

Instructional Objective Categories	Experimental group: activity based on CVI guidelines?	Control group: activity based on CVI guidelines?	Experimental Group Mean (SD) [Total Marks]	Control Group Mean (SD)	Significant difference?
1. Visualize to explain a specified concept	√	X	2.86 (0.43) [3 marks]	2.42 (0.84)	Yes (U=1853 p= 0.00)
2. Use a given visualization to solve the given problem by executing multiple processes	√	X	4.36 (1.18) [5 marks]	3.47 (1.71)	Yes (U=1883 p=0.001)
3. Write/Draw alternate representations from the given visualization or vice-versa.	√	X	2.56 (0.77) [3 marks]	1.86 (1.15)	Yes (U= 1744 p= 0.00)
4. Use a given visualization to solve the given problem by executing single process	√	√ [CVI guideline of watching with instructor commentary met]	3.34 (1.34) [4 marks]	3.51 (1.29)	No (U= 2416 p= 0.5)

6. Discussion & Conclusion

In this section we summarize the results corresponding to each research question. We then discuss the implications of the study, its limitations and scope for future research. The first research question was answered through a qualitative study covering multiple domains and a range of visualizations. Eleven categories of instructional objectives with visualizations were identified across different instructional settings. The second research question was answered by analysis and synthesis of literature. A set of instructional strategy design components, mapped to individual objectives, were identified to achieve strategic alignment. Based on this mapping, we framed guidelines for instructors to design learning activities aligned to their objectives with visualization (Table 2). CVI also offers learning designs (LDs) mapped to particular objectives. These LDs operationalize the recommended design components through a sample set of constructivist strategies (Fig. 1). The third research question was answered through a 2-group post-test only field experiment. We measured successful constructive strategic alignment through significantly better post-test scores of the experimental group which followed CVI guidelines compared to the control, for each of the objectives (Table 2). Though visualization selection is an important first step, in this paper we have focused on integration of visualization in teaching.

The contributions of the CVI framework are outlined below. The CVI guidelines and learning designs empower instructors to create theory-informed learning designs integrating visualizations and aligned with their set of instructional objectives. Thus CVI enables instructors to overcome the problem of how to effectively integrate visualization in teaching. There are, however, certain limitations to the CVI in its current form. Our sample base for identifying objectives was restricted to K -16 science and engineering instructors. The objectives included in CVI may not be exhaustive for non-science domains and K -12 instructors. Also, the objective identified may be a function of the cultural context of the study i.e. urban Indian classrooms. In such classrooms students do not have individual access to laptops within the class although they are otherwise technology savvy. Another limitation is that validation of CVI guidelines has been done in one topic and in one domain. As part of future work, the current validation experiment can be extended to include different 'Signals and Systems' topics together with topics from other domains and cover the remaining CVI guidelines. The usefulness and usability of the CVI guidelines and LDs also need to be tested with instructors. Overall, the CVI framework aims to plug the existing gap in integration of visualizations in teaching by identifying instructional objectives with visualization, providing guidelines for constructivist strategic alignment and presenting learning designs mapped to individual objectives to ensure implementation fidelity of the mapping.

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