Experience and Guidance for the use of Sketching and low-fidelity Visualisation-design in teaching

Jonathan C. Roberts[*] Panagiotis D. Ritsos[†] Christopher Headleand[‡]
Bangor University Bangor University University of Lincoln

ABSTRACT

We, like other educators, are keen to develop the next generation of visualization designers. The use of sketching and low-fidelity designs are becoming popular methods to help developers and students consider many alternative ideas and plan what they should build. But especially within an education setting, there are often many challenges to persuade students that they should sketch and consider low-fidelity prototypes. Students can be unwilling to contemplate alternatives, reluctant to use pens and paper, or sketch on paper, and inclined to code the first idea in their mind. In this paper we discuss these issues, and investigate strategies to help increase the breadth of low-fidelity designs, especially for developing data-visualization tools. We draw together experiences and advice of how we have used the Five Design-Sheets method over eight years, for different assessment styles and across two institutions. We follow our experiences with an equal measure of advice. This paper would be useful for anyone who wishes to use sketching in their teaching, or to improve their own experiences.

Keywords: Sketching visualisation designs, Five Design-Sheet, Information Visualisation, Teaching visualisation, Learning Support

Index Terms: H.5.2 [Interfaces and Presentation]: User Interfaces—Graphical User interfaces (GUI). K.3.2 [Computing Milieux]: Computers & Education—Computer Science Education

1 INTRODUCTION

Educators need to develop skills in students that are appropriate for the workplace. Visualisation techniques are being applied to all types and aspects of work. Consequently educators, in the fields of visualization and computer science, need to integrate creative tasks and engage their learners with appropriate creative content. Computer science educators, have excelled at finding strategies to teach programming and software development, but unfortunately they have less experience in instructing creative computing and design. While low-fidelity methods and sketching techniques are a key skill of some academic courses, such as architecture and design courses, they have been less used within computing education.

There are many reasons for this situation. For example, the students themselves may not see the relevance for creative computing strategies; students on a computer-science major may wish to focus on coding and not design. In fact, we have had personal experience of students saying "we code, we do not design", implying that they will not engage with any creative activity. But it is not only students that inhibit the inclusion of more creative design in the curriculum. For instance, academics who are teaching the modules, may not believe that they themselves are artistic and so can be reluctant to lead others in these skills. Subsequently they portray a negative (and so detrimental) attitude about sketching to the students. But there are many other reasons and issues too.

In this work we explore these issues, of how to integrate low-fidelity and sketching techniques in education, for the aim to develop the next generation of visualization and creative computing students. We, not only discuss where problems and issues lie, but offer guidelines and potential solutions. We draw our experiences from teaching and using the Five Design-Sheet methodology (FdS) [23–25] for over eight years both at Bangor and Lincoln Universities, and applying the Explanatory visualisation Framework (EVF) for two years [26, 29].

2 BACKGROUND & RELATED WORK

As educators ourselves our vision is to help develop the next generation of visualization designers. We wish to develop better methods and structures to help (both) educators and students. Indeed, this is why we developed the FdS and EVF methods, to help structure students and developer's work and help them to create better designs and plans. We are not alone in these thoughts. The voices of educators calling for "more design in computing" are getting louder. Robinson writes "*the world is changing faster than ever in our history . . . We need to create environments – in our schools, in our workplaces, and in our public offices – where every person is inspired to grow creatively*" [30].

In our teaching, we have been focusing on sketching designs (and in particular using the FdS and EVF structures). We acknowledge that there are other models that a student could follow, including the waterfall model which defines requirements, design, implementation, verification, maintenance, or models by Simon [33], Design Council [7], instructional models such as ADDIE [4], Jonassen [14], to Munzner's nested model for visualisation design [18], McKenna et al. [17] (understand, ideate, make, deploy) and the nine-stage design-study model by Sedlmair et al. [31]. In addition, methods such as VisitCards [12] could be used to explore the design space with users, or token and constructive-based tasks using physical objects [13] are useful for concept investigation.

We have two broad requirements, first to get students to explore the solution domain and initiate new design solutions, and second to create an artefact that they can use as a guide for their coding. These two requirements are important because they direct the methods and techniques that we use (namely sketching using the FdS methodology). Exploring the domain through sketching enables the student to examine many solutions, explore the suitability of each, and discover solutions that they originally had not imagined. These creative artefacts are used in a *problem-solving* capacity. In fact, through investigating alternatives the students *evaluate*, *synthesise* and *analyse* the problem domain. The sketches help the student to explore many solutions quickly, on paper, rather than building them in code (that would take much time and effort). Indeed, the artefacts provide a plan, that confirms the ideas in the students' mind, such that they have a clear recipe to follow. From a teachers point of view, the sketches act as a record of the thought process. This is similar to studying mathematics, where a teacher may say "write down the intermediate steps". Grades can be awarded to different sketches, which demonstrate that the student has considered potential alternative ideas, carried-out research on related concepts, considered

[*]e-mail:j.c.roberts@bangor.ac.uk
[†]e-mail: p.ritsos@bangor.ac.uk
[‡]e-mail: cheadleand@lincoln.ac.uk

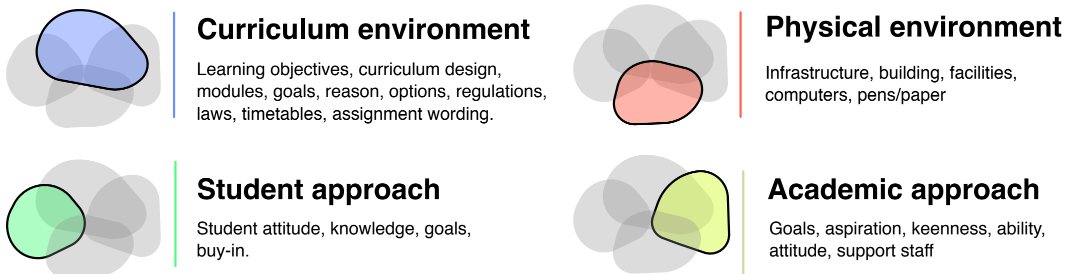

Figure 1: In an education environment, there are four principal actors that can positively or negatively affect the student experience, making them more or less likely to engage with the process of sketching or creating low-fidelity designs, as a way to contemplate alternative visualisation solutions.

usability and design best-practice, etc. The artefacts also allow the teacher to give formative feedback on intermediate sketches and plans, such to keep the student on the right learning path.

These two requirements fit into a broader set of learning outcomes. Through our creative tasks, we want to develop a breadth of skills, but particularly students should be able to: (1) *analyse* the problem domain, and create many alternative solutions (2) increase their *knowledge*, (3) be able to *synthesise* the many ideas into a few specific solutions, (4) *evaluate* and consider which alternative solutions would be appropriate, and (5) *reflect* on the appropriateness of their specific results and their whole experience. Through these learning outcomes, we are addressing the higher level skill-set of Blooms' taxonomy [15].

3 Four aspects that affect the visualization learning environment

Challenges and problems during the teaching process may arise due to any part of the *learning environment*. We explore four areas: (1) The **curriculum** and specifically the task that the students are given, which can help to engender creativity or can inhibit creative thought. (2) Students learn in a variety of **physical** settings, from formal classrooms, reading and from their peers. They have access to a range of technologies and equipment. (3) The students' attitude and the whole **student approach** to learning impinges on how they learn creative skills. Finally (4) the attitude, enthusiasm, knowledge and experience of the **academic** or teacher affects the students' learning.

Other researchers have discussed challenges of the learning environment. For example, similar to our four actors, Ramsden [21] talks about the dimensions of the learning environment, from commitment to teaching and relationships with students, workload, and formal teaching methods. Ramsden and Entwistle [11] explain that learning can be affected by *approach*, *process* and *outcome*, while Biggs [2] proposes ways to evaluate whether students are deep or surface learners. However Choy et al. [6] caution that students are not necessarily able to judge whether they are deep learners, and that the assessment itself can affect how deep the students learn. This has relevance, because we wish to develop deep learners, who are self-motivated and have a broad inter-related understanding of the field and can apply their knowledge to many different situations. It also supports that there are many factors involved in developing an appropriate learning environment.

4 Curriculum environment – the task

In an education setting we can consider many different assignments types: from those that get students to build a simple code snippet to project modules that require the student to consider requirements, make designs, perform an implementation and then evaluate the system. Some tasks are precisely defined, where the results by all students will look similar. These are *well-defined* problems. There is a clear solution path, students converge to specific answers, and all submissions are very similar. However, we are more interested with *ill-defined* problems [27], where it is less clear how to build the solution, and in fact, many solutions could be equally valid.

The scenario (and even its wording) can affect positively and negatively how students develop creative skills. The task needs to be open-ended to engender creativity, yet something that can be graded, and comparisons can be drawn between each student. In the EVF we task the students to "develop and explanatory visualization of an algorithm", see [26, 29]. We have also got the student to "choose their own dataset and create a new data-visualisation tool to display this data". Especially with the latter task, the student will need to work out what is important in the data, what aspects may be interesting and how to map the data to specific retinal variables. These are *ill-defined problems*; while there is still a specific goal [9], and the student will know that their result fulfils (or doesn't) the problem description, they need to perform *divergent* and *lateral thinking* [8] to create alternative ideas, make judgements over these ideas to create a new data-visualisation. Additionally when each student has a different dataset to follow they can share results and ideas without issues of plagiarism.

5 Physical environment

The physical environment is recognised as a significant factor for knowledge creation and learning [19, 20, 32]. In our context this physical environment includes the teaching space, whether used for seminars, lectures or lab work, the tools available for externalising the ideas, e.g., pens, paper, post-its etc., and the means to realise them, e.g., computers, software etc. All these components contribute to an infrastructure that is there to foster creativity and ultimately lead to ideas with impact:

The place. Oksanen and Ståhle [20] discuss the attributes of place (i.e., space with context) that promotes creativity: collaboration enabling, modifiability, smartness, attractiveness and value collecting.

In our experience, the place where the teaching and learning activities takes place needs to be an open space, that promotes collaboration and immediacy. Learners should be free to collaborate, discuss their work with others, feel free to take a walk to relax, clear their head and get some ideas. This approach is on par with Lippman's [16] recommendation on responsive design of learning environments, where rather than assuming a place is 'ideally' designed for learning, its advantages and constrains inform the learning process. This also fits with the aspect of modifiability of the environment, as described by Oksanen and Ståhle [20], where users can make better use of their learning space by embracing its shortcomings. Lippman [16] argues that responsive design of spaces promotes a "culture of inquisitiveness", which is intrinsic in our teaching methodologies, such as the FDS. In these, learners are encouraged to explore new ideas freely, before making decisions on their viability and appropriateness for the task at hand. At the same time, in order to provide inspiration, and promote ‘smartness’ and ‘attractiveness’, we opt to display previous work, such as visualisations and applications, as posters and banners. Our intent is to inspire and guide, as well as to demonstrate that contributions are valued and celebrated.

The materials: By materials we define non-software physical items that can be used to prototype and realise visualizations. As the FDS methodology is integral to our teaching, we use a collection of materials suitable for sketching. These include: (a) large sheets of paper (A3/ISO216 or Ledger/Tabloid ANSI/ASME Y14.1), rather than sketch-books which can be restrictive, (b) pens (felt tips, alcohol/water based pens etc.) instead of pencils. We prefer pens as they force designers to commit their ideas, instead of spending time adjusting a limited number of designs. The quality of these materials is of course of paramount importance. Much like an artist uses the best oil paints, or a scale modeller the best airbrushes and pigments, a visualization designer needs good quality pens, with, say, fine tips and consistent colouring behaviour. Quality materials also contribute to the ‘attractiveness’ of the outcomes, whereas the also imply a level of ‘smartness’ due to their good quality and ‘professional’ feel.

The technology: An important aspect of the environment is the technology available to learners, both for creating their prototypes, as well as for realising their final, implementations. We feel it is essential for a learning space to provide access to a number of technological resources, from (mandatory) web access, to contemporary libraries and applications for building visualisations. In practice, learners often have to work with pre-selected applications, installed in a lab by a university’s IT services. However, in particular in the domain of visualization, the number of open-source, web-based libraries and tools allows great flexibility, while providing contemporary and cutting-edge tools for implementing visualizations.

Moreover, our perception of space and place is constantly changing due to technological advancements [22]. We have stopped associating activities with a particular space (e.g., checking our emails on our workstation at home), as we have constant and ubiquitous access to resources, such as cloud stored files, email etc. We now collaborate in shared virtual spaces, whether these are part of an institutions teaching provision such as virtual learning environments (VLEs), or through social media (e.g., Facebook groups, Slack etc.). In the future we may be teaching and learning in immersive environments [28], designing prototypes with tools that evolved from contemporary applications such as Google’s Tilt brush. However, despite this shift in our perception of physical space, we expect the basic principles of spaces that foster learning, creativity and innovation will not change, as these are human-centered and socio-technical [1].

6 Student approach

Encouraging students to sketch and prototype in a creative fashion can be a challenge. For some students, drawing is simply not part of their leaned skill-set, and they find its use daunting. This is especially overwhelming for perfectionist students, who may see their own artistic ability as poor and possibly a personal failing. Indeed, we have seen a number of students throw away perfectly good designs because “they were not neat enough”. Others struggle to engage as they are more familiar with other mediums (such as computer drawing), or simply do not see the value of the sketching approach. We have also known students to express an attitude of annoyance at having sketching imposed upon them on a computer science course. The “I came here to code” position is sadly not uncommon. We can split these barriers down into four distinct issues, which we will categorise according to the following terms; knowledge, experience, attitude, and fear of failure.

Knowledge. When young children learn to communicate, they regularly do so through creative outlets. Often a child will paint, and crudely illustrate before they are able to write. However, this natural tendency is often less encouraged by educators, in favour of written or verbal. Perhaps the world would be a different place if we evaluated education by sketching and drawing, rather than using writing. In the British education system, students are expected to specialise their learning at 14 when they choose their GCSE examination subjects. This is further narrowed down during their A levels (typically between 16 and 18 years old), followed by a single subject for their degree. Similar models are practised in a number of countries worldwide. In comparison, all subjects would have required the student to communicate through writing, with less importance on drawing. When students are expected to sketch and draw (such as drawing geographical processes or chemical symbols) there is little teaching on how their sketches should look, how best constructed, how much detail is required and how to make them more aesthetically pleasing. The emphasis, rather, is that they are visually readable, clear and contain the correct functions. Sketching and design skills are excluded from most subjects. This leaves a number of students without the knowledge, and conceptual tools required visualise in this manner.

In our experience we overcome this issue by delivering basic instruction on sketching. We run workshops sessions dedicated to basic drawing skills. E.g., drawing lines, boxes, shading cubes and cylinders, sketching creative alternatives. There are a number of excellent books which cover basic sketching techniques, including chapter 5 “Sketching Design Skills” [25], Buxton [5] and drawing skills [10]. Some students also find non-permanent mediums (such as dry-wipe surfaces) useful to build their creative confidence. However, while this may be useful in developmental exercises, we generally advise permanence when considering drawing mediums (which will be discussed in the following section).

Experience. Related to the issue of *knowledge* is that of experience. Using sketching as a tool requires some practice. Students may be intimidated by the idea of applying a tool that they may not have actively used. It is important to ensure that students understand that when sketching in this manor, what is important is the communication of the idea, not the artistic impression of the drawing. This is an issue we have faced a number of times, students are often more personally concerned with artistic realism or the neatness of the drawing that they forget the purpose of the activity. As aforementioned we have seen a number of students erase or discard perfectly good concepts for fear that they did not meet a certain graphical standard. Students also need to learn that if they do make a mistake, they should incorporate that error in their design. If it is something absolutely wrong, then to use a simple line to cross-out the design. Students also learn through experience how to place the graphical marks on the page – they need to first imagine (envision) how the end result will look, and where sketches could go on the page.

One method we have used to modify this behaviour is the use of permanent mediums. For example, instead of providing individual pieces of paper, the students could be provided with non-perforated notebooks (where pages cannot be neatly removed). Instead of pencils that can be erased, the students should use felt-tip pens. When students are working in this way we have noticed that they tend to take a little more time considering what they are about to commit to paper. They also quickly get used to the idea that once something has been drawn, it is permanently recorded. As such, artistic quality is less of a reason to discard an idea, and if a student moves on, it is to draw something else. However, experience is always a significant issue when working with computer science students. Ultimately, the best way to overcome this issue is through the facilitation of activities that allow them to develop their sketching skills. Sketching confidence/visual communication exercises can also be useful. For example, picture charades-inspired games (e.g., Pictionary) encourage students to visualise a concept quickly in front of peers.

Attitude."Why do I have to draw?" this quote is not from any one specific student, but an amalgamation of student comments over the years. The reality is that the perception of what a student *thinks* they should be learning is not always reflected in what they *need* to be learning. It is not uncommon for computer science students to believe they are at University to learn programming and nothing else. Even those on the data-visualisation course want to jump straight into coding. This is not a problem faced only for sketching, but also items like soft skills and maths. Students need to buy-in to the activity. Some students simply do not value sketching as a skill relevant to their chosen industry. Students that buy-into the concept, are enthusiastic, and engage with the application will always gain more from the experience. However, how do you motivate students to commit to the topic?

Overcoming a negative attitude is difficult, as the student may simply have no interest in sketching or design and could ignore any proposed argument or benefit. One way we have tackled this issue is by highlighting the need for visual representation of certain concepts, by taking a student centric approach. In one lesson we asked the students (in groups) to write and describe the design of an interface in a way that another student could interpret and potentially implement it. The purpose of the exercise is highlight the limitation of written communication for visual mediums. Within five minutes we had a number of students asking if they could use diagrams within their description to explain some of their ideas. After attempting the exercise for 15 minutes the students were engaged in debate about the challenges they faced, and what the solutions could be. The students unanimously chose to sketch, and we had little negative comments onward: they had naturally concluded that sketching was beneficial through their own experience. In addition, providing an industrial contextualisation has a significant impact on buy-in. Relating the students learnt skills back to activities that they will be undertaking in their career makes the experience more real and relevant. This can also be supported by invited talks from employers. It is worth noting that attitude may also simply be a symptom of poor knowledge and limited experience (as discussed in the previous two items).

Fear of failure. Sometimes students do not know where to start, or how to get a good grade in their assessment; they have a "fear of failure" and as such do nothing or very little. Especially for creative assignments they may not know realise how to get a good mark; for other assignments they perhaps have relied on memory to regurgitate facts rather than learning the content deeply [11]. These students have a legitimate concern, because creative assessments are graded on breadth, diversity and type of ideas rather than reiterating standard ideas, and indeed there need not be any "standard ideas" that have been previously created that could be copied!

Students should be allowed to fail and encouraged to recover. This is important in the creative field of visualization as students learn creative tasks through experience. They need to actively take part in activities and try out techniques such to hone their skills. We have employed two principal solutions: (1) we provide ongoing (weekly) *formative feedback* (i.e., oral feedback from the instructor that is timely, positive and explains how they can improve their work), and (2) to allow students to *re-submit*. Students can resubmit many times, but each time they submit they lose 10% of that grade. Their final grade is calculated to be the highest grade. This improves the grades of fearful or failing students, yet reduces the quantity of resubmissions because it is not beneficial to students who are achieving 60% or more.

7 Academic Approach

Challenges of creative design in visualization are influenced also by the academic, teacher or tutor delivering the material. We focus on attitude, understanding, and time and effort.

Educator's Attitude. It can be very easy for an educator to be negative about a course: an attitude either explicitly or implicitly saying: "this will not be useful, but you have to do it" will not encourage the students to sketch alternative designs and explore different visualization ideas. Having a positive attitude is essential. It is not always easy, teachers get tired, and can be under immense time pressure. But, quash negative thoughts, see possibilities in others, see worth in what you do, have fun with the activities you do with the students.

Understand your students – tuned in. Educators need to be sensitive to diversity, they should acknowledge that students are all different, come from various backgrounds experience and have different motivations. Students learn through different methods; some students quickly realise what is required, whereas others struggle with simple concepts; some take a holistic approach, whereas others favour a step-by-step approach. Ideally we want students to have a good experience, and to be located within a good learning environment; that they know what they need to do, have the skills to do it, discover any missing knowledge on their own, know how to apply it to their situation, and provide a successful result. To have deep learners, rather than surface learners.

To overcome issues in our visualisation modules we have tried to see the world through their eyes. It is not always easy to understand their world, as educators get older they become more distant from their own formal education. But reflection and empathising with the students can help. Do you know your students? Do you know what they know? Do you know about their pressures (e.g., other assessment deadlines?) Do you know what expectations they have with your teaching? What do they know already in visualization? Do you know which students are creative, and which ones will struggle with your creative tasks? Visual literacy is an important aspect to data-visualisation design, and evaluating the students for their visual literacy may help you understand the students better [3].

Time and effort. It is important to give ongoing feedback to students as they develop their sketches and creative visualizations, but this takes time and effort. Especially with large class sizes it can be difficult to talk to all students.

Ideally we want to give each student some feedback every week, but practically this would depend on the class size. First, we encourage students to reflect on their own work, and to talk and discuss their work with other students. Being able to critique other students design ideas are good skills to learn. Second, we give every student a different task (e.g., a different dataset to visualise); they can readily share ideas and techniques without problems of plagiarism.

8 Conclusion

Creative skills are important in data-visualization, and sketching skills have an important place in computer science education. We acknowledge that understanding creative skills is only one aspect towards developing the next generation of data-visualisation designers and developers. In addition, students need to develop coding skills, understand perception, know how to develop GUI interfaces, and how to manage client interaction and project management. Sketching and creative thinking, however are skills that has been largely ignored in computing education. In this paper we have started to address some of the challenges and we provide pragmatic answers to integrating sketching and creative thinking for visualisation in the computer science curriculum.

References

[1] L. Bannon. Reimagining HCI: Toward a more human-centered perspective. *interactions*, 18(4):50–57, July 2011. doi: 10.1145/1978822.1978833

[2] J. Biggs, D. Kember, and D. Y. Leung. The revised two-factor study process questionnaire: R-SPQ-2F. *British journal of educational psychology*, 71(1):133–149, 2001.

[3] J. Boy, R. A. Rensink, E. Bertini, and J. D. Fekete. A principled way of assessing visualization literacy. *IEEE Transactions on Visualization and Computer Graphics*, 20(12):1963–1972, Dec 2014. doi: 10.1109/TVCG.2014.2346984

[4] R. K. Branson, G. T. Rayner, J. L. Cox, J. P. Furman, and F. King. Interservice procedures for instructional systems development. executive summary and model. Technical report, DTIC Document, 1975.

[5] B. Buxton. *Sketching user experiences: getting the design right and the right design*. Morgan Kaufmann, 2010.

[6] J. L. F. Choy, G. O'Grady, and J. I. Rotgans. Is the study process questionnaire (SPQ) a good predictor of academic achievement? examining the mediating role of achievement-related classroom behaviours. *Instructional Science*, 40(1):159–172, Jan 2012. doi: 10.1007/s11251-011-9171-8

[7] D. Council. Eleven lessons: managing design in eleven global companies desk research report, 2007. www.designcouncil.org.uk.

[8] E. De Bono. *Lateral Thinking: Creativity Step by Step*. Penguin, 2009.

[9] K. Duncker and L. S. Lees. On problem-solving. *Psychological monographs*, 58(5):i, 1945.

[10] B. Edwards. *The New Drawing on the Right Side of the brain*. Tarcher, 2012.

[11] N. Entwistle and P. Ramsden. *Understanding Student Learning*. Routledge Revivals, 1983.

[12] S. He and E. Adar. Vizitcards: A card-based toolkit for infovis design education. *IEEE Transactions on Visualization and Computer Graphics*, 23(1):561–570, Jan 2017. doi: 10.1109/TVCG.2016.2599338

[13] S. Huron, S. Carpendale, A. Thudt, A. Tang, and M. Mauerer. Constructive visualization. In *DIS 2014: Proceedings of the ACM conference on Designing Interactive Systems in 2014*, pp. 433–442. ACM, 2014. doi: 10.1145/2598784.2598806

[14] D. H. Jonassen. Instructional design models for well-structured and ill-structured problem-solving learning outcomes. *Educational Technology Research and Development*, 45(1):65–94, 1997.

[15] D. R. Krathwohl. A revision of bloom's taxonomy: An overview. *Theory into practice*, 41(4):212–218, 2002.

[16] P. C. Lippman. Can the physical environment have an impact on the learning environment? *CELE Exchange, Centre for Effective Learning Environments*, 13, 2010. doi: 10.1787/5km4g21wpwr1-en

[17] S. McKenna, D. Mazur, J. Agutter, and M. Meyer. Design activity framework for visualization design. *IEEE Transactions on Visualization and Computer Graphics*, 20(12):2191–2200, Dec 2014. doi: 10.1109/TVCG.2014.2346331

[18] T. Munzner. A nested process model for visualization design and validation. *IEEE Transactions on Visualization and Computer Graphics*, 15:921–928, Nov 2009. doi: 10.1109/TVCG.2009.111

[19] I. Nonaka and N. Konno. The concept of "ba": Building a foundation for knowledge creation. *California Management Review*, 40(3):40–54, 1998. doi: 10.2307/41165942

[20] K. Oksanen and P. Ståhle. Physical environment as a source for innovation: investigating the attributes of innovative space. *Journal of knowledge management*, 17(6):815–827, 2013.

[21] P. Ramsden. Student learning and perceptions of the academic environment. *Higher Education*, 8(4):411–427, 1979.

[22] P. D. Ritsos. Mixed Reality - A paradigm for perceiving synthetic spaces. In M. Reiche and U. Gehmann, eds., *Real Virtuality*, pp. 283–310. Transcript-Verlag Bielefeld, 2014.

[23] J. C. Roberts. The Five Design-Sheet (FdS) approach for Sketching Information Visualization Designs. In S. Maddock and J. Jorge, eds., *Proc. Eurographics 2011 – Education Papers*, pp. 27–41. The Eurographics Association, 2011. doi: 10.2312/EG2011/education/029-036

[24] J. C. Roberts, C. Headleand, and P. D. Ritsos. Sketching designs using the five design-sheet methodology. *IEEE Transactions on Visualization and Computer Graphics.*, 22(1):419–428, Jan 2016. doi: 10.1109/TVCG.2015.2467271

[25] J. C. Roberts, C. J. Headleand, and P. D. Ritsos. *Five Design-Sheets – Creative design and sketching in Computing and Visualization*. Springer, 2017. doi: 10.1007/978-3-319-55627-7

[26] J. C. Roberts, J. Jackson, C. Headleand, and P. D. Ritsos. Creating Explanatory Visualizations of Algorithms for Active Learning. In *Posters presented at the IEEE Conference on Visualization (IEEE VIS 2016), Baltimore, MD, USA*, October 2016.

[27] J. C. Roberts, D. Keim, T. Hanratty, R. Rowlingson, R. Walker, M. Hall, Z. Jackobson, V. Lavigne, C. Rooney, and M. Varga. From Ill-defined Problems to Informed Decisions. In M. Pohl and J. Roberts, eds., *EuroVis Wkshp Visual Analytics*, pp. 7–11. Eurographics, 2014. doi: 10.2312/eurova.20141138

[28] J. C. Roberts, P. D. Ritsos, S. K. Badam, D. Brodbeck, J. Kennedy, and N. Elmqvist. Visualization beyond the desktop–the next big thing. *IEEE Computer Graphics and Applications*, 34(6):26–34, 2014. doi: 10.1109/MCG.2014.82

[29] J. C. Roberts, P. D. Ritsos, J. R. Jackson, and C. Headleand. The explanatory visualization framework: An active learning framework for teaching creative computing using explanatory visualizations. *IEEE Transactions on Visualization and Computer Graphics*, Jan 2018. Accepted for publication.

[30] K. Robinson. *The Element – how finding your passion changes everything.* Viking Penguin, 2009.

[31] M. Sedlmair, M. Meyer, and T. Munzner. Design study methodology: Reflections from the trenches and the stacks. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2431–2440, 2012.

[32] D. Senoo, R. MagnierWatanabe, and M. P. Salmador. Workplace reformation, active ba and knowledge creation: From a conceptual to a practical framework. *European Journal of Innovation Management*, 10(3):296–315, 2007. doi: 10.1108/14601060710776725

[33] H. A. Simon. The structure of ill structured problems. *Artificial intelligence*, 4(3-4):181–201, 1973.