

Pair Analytics in a Visual Analytics Context

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Abstract

This case study details the development of “pair analytics” as practical approach to applied analysis and as a scientific research method. The hybrid research project itself was part of a larger research program approved for the Canadian government for their offset program and supported by Federal and Provincial research internships. As a real-world analysis approach, the pair analysis sessions conducted actionable causal chain analysis of aircraft safety. As a scientific method, pair analytics advanced our knowledge of the cognitive science of interpersonal communication in Joint Activities. The paper describes how aerospace researchers and cognitive scientists were able to design a research approach that met constraints from both areas. It concludes with discussion of the implications of this work for highly integrated basic and responsive research in other areas of visualization and analytics.

Keywords: pair analytics, visual analytics, technology insertion.

1. Introduction

As our ability to collect, preserve, and access data has grown, data analytics has become increasingly important. Computing has only exacerbated the data collection problem. Devices (e.g., robots, sensors, medical devices, telescopes) and people generate more and more data, leading to the world of 'Big Data' (Press, 2013).

Data analysis in one form or another has existed since the early days of mankind. The sheer amount of data overwhelms conventional, manual techniques. Therefore, businesses and government agencies have pushed to generate computer programs to assist data analysts using conventional techniques (e.g., statistics). Visual analytics, which relies on visually enabled reasoning (Meyer et al, 2010) proposes a “science of analytical reasoning facilitated by interactive visual interfaces” (Thomas & Cook, 2005) to support analysis interface design.

As is the case with any promising new technology, a substantial amount of effort is required to move it into more common practice. This paper is a case study of the evolution of a joint industry-academic research program to transition visual analytics into a large aerospace company, Boeing.

This paper describes the transition in terms of developing a process the authors named 'pair analytics' (Arias-Hernandez, et al 2011, Kaastra et al 2014). There was no indication in the development of the field of visual analytics that pair analytics would be effective, and the pair analytics concept was developed as part of the joint industry-academia research program. The program resulted in additional advances (Boy et al 2014, Kadivar et al 2009, Rensink et al 2014, Rensink et al 2017).

The case study documented here describes pair analytics in the context of the overall joint program design and development. The evolution of the program is described in general, including a focus on pair analytics and lessons learned.

We deliberately organized the paper in a non-traditional manner. While the general topics are similar to many other papers, we separated the industrial and academic components in each major section and derive overall lessons learned. This allows readers to follow the progress and challenges from both a funding agency/customer and from an academic institution/provider independently. We observe that understanding both industrial and academic sides were essential in the project's success.

2. Background

Starting a program, especially one that has no precedent, brings a unique set of challenges. The joint Boeing-university program was no different.

2.1 The industrial perspective

Throughout its history, Boeing has been at the forefront of adopting new computing technology (Dill & Kasik, 2012). Fundamentally, Boeing uses any technique possible to remain as a leader in aerospace technology. In so doing, staff members are often involved in advanced topics that range from computer-based human models to fractal geometry to massive model visualization. This led to Boeing staff involvement in visual analytics during the definitional and conceptual phases of the field (Thomas & Carr, 2005)

As Boeing staff became more aware of visual analytics capabilities, they performed early comparisons of visual analytics to more traditional analysis methods (e.g. statistics). One set of comparisons, which are only available internally, showed that a relatively new analyst using advanced visualization tools could identify maintenance condition outliers more reliably than an analyst could when using more traditional methods.

Internal interest increased further after the analyst reviewed the results with airplane maintenance experts. Some of the reported conditions were surprises the experts had not been able to identify on their own. The results were so encouraging that the team doing the comparisons looked to expand the project and find a way to accelerate new technology adoption.

There were two immediate problems: 1) Finding staff with the skills and, more importantly, the time to work on the project, and 2) finding and allocating funding. The search took six months. At that time, the team identified an unexpected solution.

International corporations, especially those who supply defense systems to governments, are faced with numerous, complex rules and regulations. The team discovered that Boeing is often bound by Industrial Participation agreements, that can be defined as "provisions to an import agreement, between an exporting foreign company, or possibly a government acting as intermediary, and an importing public entity, that oblige the exporter to undertake activities in order to satisfy a second objective of the importing entity, distinct from the acquisition of the goods and/or services that form the core transaction." (Offset Agreement (2022-08-25)) in https://en.wikipedia.org/wiki/Offset_agreement.

In other words, a government buying imported products requires the exporting company to buy local goods and services.

Boeing has long supplied defense systems to Canada. Canada requires all defense suppliers to have Industrial Participation agreements. There are many ways to be a Canadian Industrial Participant (e.g., purchase goods and services, hire Canadian citizens in local offices, invest in start-up efforts, fund research with Canadian universities). Canadian Industrial Participation in university research features a credit multiplier greater than one. The policy is intended to keep Canada at the forefront of new technology. Canada purchased Boeing C-17 transports and required Industrial Participation. In short, Boeing had to figure out how to spend money in a way that would benefit both Boeing and Canada.

Canadian researchers contacted the Boeing visual analytics staff about Industrial Participation. Boeing staff realized that a research program with quality Canadian researchers using Industrial Participation funding would address the staff and funding issues stalling visual analytics transition. The technical staff quickly found Boeing Industrial Participation points of contact. Funding was available and quickly allocated. While contracts were negotiated, professors at Simon Fraser University and the University of British Columbia (both in Vancouver BC) started generating student interest in visual analytics.

The final step was putting contracts in place. In this situation, neither Boeing nor the Canadian universities had started similar programs. This turned out to be beneficial because upper levels of Boeing management considered the program to be experimental and waited to see what would happen. As a result, the team developed a mutually agreeable statement of work and a contract was put in place within six months. The joint SFU/UBC grant was titled "Boeing Support for Visual Analytics in Canada". As the name suggests, the project included support for the generation of knowledge about visual analytics that could be applied in other contexts,

contribute to educational programs etc. An equal weight was placed on the joint production of analysis of real-world aircraft manufacturing, safety, and reliability conducted with expert analysts and real data. It was then up to the team to develop a five-year program that would achieve these goals and that would result in development and transfer of new, advanced technology and analysis methods from the academic environment into a large and complex company.

2.2 The Academic Perspective

Putting a 5-year program together with a single institution is difficult enough. Here both institution's contracts departments needed to be signatories. To simplify negotiations, UBC became prime and SFU a subcontractor. Rather than to place the grant in a computing or engineering department we chose to run the Boeing project in the UBC Media And Graphics Interdisciplinary Centre. As an endowed research centre, MAGIC was able to set up a research management structure for the project that included representatives from both universities. The university contracts staff had not previously dealt with this type of project. Despite the lack of experience, the project was defined and formal documents signed within 6 months.

Our research group consisted of senior faculty members from the two universities with affiliations in Psychology, Computer Science, and the interdisciplinary School of Interactive Arts and Technology. They brought to the project experience with fundamental, translational, and applied research. As the project continued, other faculty researchers received funding for work conducted on specific projects.

Boeing's openness to innovation in research methods and outcomes provided the university researchers with the unique opportunity to combine basic and application work in a single project. To have done this on government funding would require coordinated proposals to programs in basic (e.g. the Natural Science and Engineering Research Council Discovery Research Program), translational (e.g. NSERC Strategic Partnership Program), and application (e.g. NSERC Collaborative R&D Program). While innovative by many measures, these programs can in practice create "silos" of basic and responsive research. This is largely due to the program's goals and funding criteria. For example, "basic science" NSERC Discovery proposals are assessed for their contribution to knowledge in the general sense. These basic research projects may set the stage for a follow-on Strategic Partnership Project. Strategic Partnership proposals must focus on an area that is deemed to be strategic for Canadian industrial competitiveness. They are reviewed for their translation and adaptation of basic research to support later application work by an industry partner. If this follow-on work also involves university collaboration matching programs such as the NSERC Collaborative R&D and MITACS (Mathematics of Information Technology and Complex Systems) Accelerate grants can combine with industry funds to support student interns working closely with the industry partner.

In contrast, the Boeing project was not divided into separate fundamental, translational, and applied components, but instead would support researchers to integrate fundamental and applied work into a coherent research program. The high level of integration of basic and responsive research in the project enabled it to become the

keystone of a coordinated research program that included supplemental basic, translational, and application grants and internships from NSERC and MITACS.

A second factor that supported the integrative aspect of the project was the interest in methodological innovation in the field of visual analytics. Visual analytics begins with the claim that interactive visual interfaces can play an important role in analysis, and that a science of analytical reasoning should be developed to guide the development of human-in-the-loop analysis systems. Early on, visual analytics research was often seen as translational, applying cognitive psychology theory to analysis and interaction design (Fisher et al 2011). As the field matured it became apparent that the complex cognitive processes of skilled analysts (e.g. aerospace experts) using advanced visualization and analysis technologies would require its own research methods (Weber et al 2011). This community provided some of the first publication opportunities for our pair analytics papers.

3. Getting Pair Analytics Started

As is the case with many programs, getting started proved the most difficult part. In many ways, the start-up challenges in both industry and academia motivated our development of the pair analytics approach.

3.1 Industrial Start-up Challenges

The program started reasonably smoothly. There was adequate funding and a shared desire to explore new frontiers in visual analytics. The formal statement of work was deliberately flexible because of the immaturity of the technology and understanding how to work together. The working together part was straightforward to address because both industry and academic teams had developed a long-term relationship and respect at numerous professional conferences.

The industrial technical program manager quickly established a consistent communication rhythm scheduling biweekly 60-minute check-in calls and twice-yearly face-to-face review meetings. The calls allowed the three primary professors and Boeing staff to monitor short-term progress. The reviews provided more in-depth project content understanding and direct contact with both professors and students.

The first six months was spent further refining project goals and determining how to allocate academic funding. The time was also needed to attract students and define specific tasks for them.

Doing so required providing data and visual analytics tools. Visual analytics tools were acquired easily because grant funding was available. On the other hand, while Boeing had lots of data, the vast majority of it was impossible to send outside the company because of proprietary concerns. Working with international universities complicated providing internal data because of export and military restrictions. The solution was finding an 'interesting', publically available data source meaningful to the aerospace industry.

Boeing project staff contacted a number of different internal groups and discovered that multiple groups rely on

external data. The most interesting and pertinent data set involved airplane safety. Boeing safety staff analyses data from dozens of different sources to assist in accident or incident occurrences. Safety is the one area where Boeing and competitors (e.g., Airbus) freely trade proprietary information. Aviation policy requires all occurrences to be documented in Aviation Safety Reporting System (ASRS, see <https://asrs.arc.nasa.gov/search/database.html>).

In addition to piquing student interest, using ASRS put technical staff in direct contact with Boeing commercial airplane safety experts. Boeing technical staff was able to introduce safety experts to visual analytics. Since visual analytics was so new, the safety experts did not want to use visual analytics tools immediately. They were comfortable using Excel-based scripts Dill & Kasik 2013).

At this point, students could start. The instructions they received were simple: Use visual analytics tools to find something 'interesting' in ASRS, the approach Boeing staff used with the demonstration project. As reported in bi-weekly conference calls, students floundered. Pilots write safety reports in a cryptic manner, students don't understand the jargon, and of course there is a mountain of data.

The program team discovered a straightforward solution. They asked safety experts to define an unsolved problem students could understand. The safety experts responded enthusiastically and suggested that the students discover ASRS evidence for causes of 'runway excursions,' occasions when an airplane leaves a runway on either takeoff or landing. The students, who had to investigate individually, responded just as enthusiastically. All attacked the data, summarized results, and presented their observations to the safety experts.

From a conceptual perspective, this approach was step one in defining pair analysis. The program team realized that data was necessary but not sufficient. People who understood the data and could define problem(s) and evaluate results were essential. Pair analysis was designed to make visual analysis more straightforward to deploy by pairing a domain subject matter expert and a visual analytics expert to work together in an analysis session. From a practical point of view this enabled the analysis to be done despite a lack of experience in the use of advanced visualization systems by aerospace analysts. Pair analysis was also designed to support capturing reasoning processes in visual analysis in the form of "pair protocols" (Arias-Hernandez et al, 2011) for later protocol analysis.

The next step in transitioning the technology involved direct experimentation with the pair analysis methodology. The program team decided to understand and evaluate the methodology to increase the probability of a successful production

3.2 Academic Start-up Challenges

Starting a large research program with two universities requires careful coordination and funding allocation. The three faculty principal investigators (PIs) coordinated funding, publications, and research methods to enable them to use complementary research approaches. For some projects, researchers took a translational approach, conducting basic research on topics that emerged from applications such as perception of statistical properties in scatterplots (Rensink, 2017). Analyses of scientific

productivity often conclude that this kind of application-aware basic research can be highly productive in generating new knowledge (Stokes, 1997, Sarewitz, 2016). These studies provide much of the scientific groundwork for our application studies and our design of visual information systems. A second research thread took a design approach to build advanced visualization systems to better support human performance in analysis. This led to the CZSaw decision-support tool (Kadivar et al, 2009).

Our third approach began with the generic analysis process described by Card and Pirolli, seen in Figure 1. We used this as a basis for extracting cognitive subtasks from analysis videos and session logs. We believed that these subtasks might shed light on analytic tradecraft skills that might transfer to other tasks and datasets. We structured our pair analysis task sessions as field experiments where dependent measures could be extracted from, and experimental probes could be introduced into, the analysis process. In addition to the Card and Pirolli work, we drew from distributed cognition frameworks (Hutchins, 1995; Hutchins et al 2013; Kirsch, 2010), applying theory and methods from psycholinguistics (Joint Activity Theory (Clark, 96; Brennan & Hanna, 2009) and cognitive ethnography (Arias & Fisher, 2014). As a hybrid of observational and experimental methods, pair analysis was integrative in that a single study could generate data that could be used to test cognitive theory, generate new research questions for laboratory studies, and as this same time could provide insight into Boeing analysis processes that could inform the design of applications and the training of expert visual analysts in universities and at Boeing.

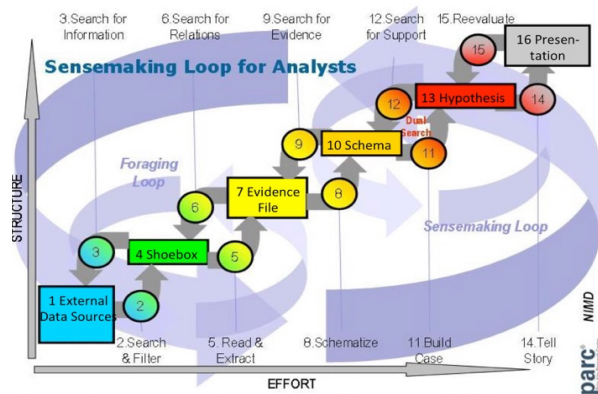


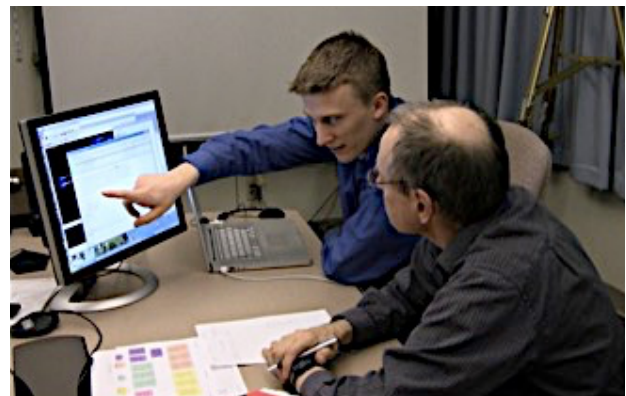
Figure 1. Generic Analysis Process

A preliminary version of these research approaches were sketched out in a research plan that began as a rough outline and became more detailed as the program evolved. One challenge that we faced in this project was the scope of the theory and methods that would be needed to understand the complexity of Boeing analysis and the ASRS datasets. To do this we employed postdoctoral scholars, one from an integrative cognitive science program and a second from an applied social science (Science and Technology Studies). These scholars coordinated the efforts of students from psychology, cognitive science, computing, and interactive arts and technology.

One concern was how we could best provide the opportunity for our project work to lead to graduate Masters theses and Doctoral dissertations in these diverse fields. Our Postdoctoral RAs needed publications that would advance their academic careers within a specific field. This was a particular concern for RAs from the social and cognitive sciences. For them, research publications in technical conferences and journals would not be as valued as those in disciplinary venues. We worked to insure that RA work would be based on current theory and methodologies in the appropriate field and would be accomplished on a time scale appropriate for a given academic program.

Individual sub-projects began through discussion of possible goals, datasets, and analytic technologies with Boeing stakeholders. We then identified an individual or group of Boeing analysts to work with. Only after the project goals, participants, technologies and datasets were identified did we seek ways to adapt the analytic situation so as to provide scientific data.

4. Mid-term Report



A critical part of any multi-year program is observing how it evolves. In this case, the joint program grew rapidly and collaboratively in both industry and academia.

Expanding in industry

The program's first year was typical. There were false starts and incorrect assumptions that had to be addressed. The strong teaming relationship between industry and academia proved crucial in changing direction. There was increased recognition that analysts needed more than data and tools to succeed. Problem definition, data understanding, and subject matter expertise all became requirements.

From the work done on the runway excursion problem, the program team realized that analysts could be effective when the right prerequisites were in place. The next issue was accelerating the analysis process itself. Short turnaround times are often essential in industry, especially in cases where safety and security are involved.

The program team had numerous discussions on how to make this happen. There were a number of different alternatives, especially when the analysts were university students 150 miles from subject matter experts. The team decided that the model used for runway excursions (define a problem, send it to the student analysts, occasionally check

The bird strike project was the program's first successful Pair analysis project. Andrew developed a minimally invasive technique to work with Roger. Roger identified a specific problem (e.g., use kinetic energy of a strike to identify the most dangerous bird species, how should pilots react to a strike, the least strike-prone position on an airplane fuselage for a radar antenna) and preferred datasets. Andrew gathered the data (data sources shown in Figure 2) and prepared it for analysis.

work by members of the scientific and technical communities who have proposed an increased emphasis on Highly Integrated Basic and Responsive (HIBAR) research (Whitehead, L., Slovic, S. and Nelson, J, 2020). HIBAR should be characterized by the work of multidisciplinary teams that coordinate the invention of new technologies and the discovery of new knowledge (Narayanamurti & Odumosu, 2016). This approach has attracted the interest of many in the visualization community and has led to panels and position papers that argue that a HIBAR approach to visualization research will prove fruitful (Weber et al, 2017).

Seen from this perspective the opportunities provided by the Boeing project were instrumental in the evolution of a HIBAR approach in our group. Active engagement of Boeing enabled us to advance from the translation of scientific methods and theory to integrative science, where a single project activity might contribute to advancement of knowledge in a basic research area such as cognitive science and contribute to a change of practice in Boeing. If successful, this approach to research would itself be a contribution to the community. A book describing an approach to this (Shneiderman, 2016) arrived late in the project. It was very consistent with our experience and will play a role in our future work.

Our Pair Analytics methodology naturally moved in the direction of HIBAR. Pair analytics addresses the limitations of traditional protocol analysis methods by structuring the analytic task as a "joint activity" conducted by a pair of analysts with different analysis skills and complementary roles in the process. The first role is that of a "visual analytics expert" (VAE), normally a graduate student or postdoctoral RA who is trained in analytical reasoning, the interpretation of visualizations, and fluent interaction with visual information in analysis tasks. The Boeing analyst takes the role of a "subject matter expert" (SME) whose deep understanding of the domain motivates and structures the process. From a cognitive science perspective, pair analysis distributes the cognitive task across two people who coordinate their efforts with a shared visualization environment, performing their specific cognitive subtasks as part of a "joint activity". The SME's rich conceptual and procedural mental model of aircraft and operations is more easily focused on the task and dataset through the VAE's skills in interaction with the visual information system. The VAE's skills include perceptual expertise in parsing complex visualizations ("visualization literacy"), critical thinking skills, and fluent interaction with applications such as Tableau and IN-SPIRE. Our video analysis captured how SME and VAE coordinated their individual subtasks in language, gesture, and through the use of the interface as a signaling device.

Analysis of these sessions uses Joint Activity Theory (JAT). JAT is a framework for observational research pioneered by Herbert H. Clark (Clark, 1996) and advanced by Susan Brennan (Brennan & Hanna, 2009). To implement JAT, a researcher video records a face-to-face conversation in an environment and examines it for evidence of coordination activities such as signaling, turn-taking, balance, periodicity, project markers, gestures etc., (Figure 4). Through the use of these cues, participants are able to achieve "common ground" and coordinate their actions to achieve a common objective. The majority of such studies

take place in everyday environments with goals that might be as simple as purchasing items in a drugstore.

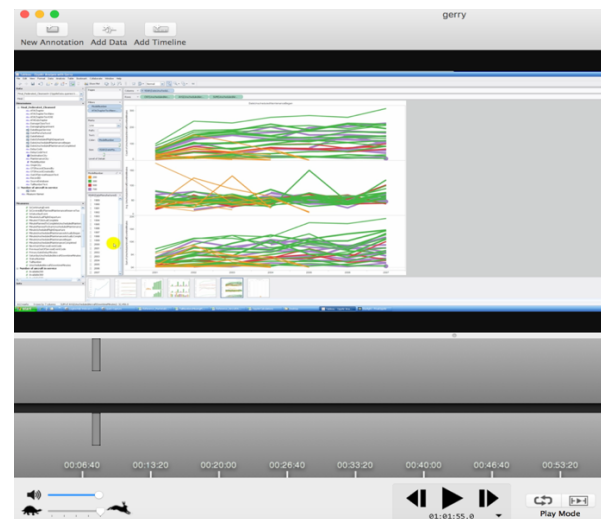


Figure 4. Post-hoc Video Analysis

Because much of the communication in our analytic task was grounded by shared graphical depictions of data, new communication markers had to be developed that would enable us to understand joint analytic activities. Similarly, gestural markers were often made using interface gestures such as circling an item with a cursor. This required extensive redevelopment of our coding strategy from the ones used by Clark and Brennan (Kaastra & Fisher, 2014). Through the development of these new codes and the use of more familiar ones, we were able to document the process by which our subject matter expert and visual analytics expert achieved common ground, advanced their analysis, and learned something of each other's expertise in performing their joint analysis task.

5.1 Evaluation

As the program drew to a close, the industry and university teams identified pieces of the program that were successful and not so successful.

6. Industrial Success

As the program began to wind down, the authors started examining its overall impact. There was clear recognition that individual projects had benefitted from pair analysis. Was using an industry - academia partnership an effective way to transition technology, especially at the corporate level?

There was clear success in the case of targeted benefit. The program generated results for real and significant business problems. It also generated substantial industrial participation credits. Boeing hired over ten analysts who received their first exposure to analytics through the program and accepted the pair analysis concept.

The program ran smoothly. The Boeing technical program manager and university PIs modified schedules and

deliverables as problems were identified and addressed. The idea was that this was a research, not a development, program. Students had to report results at all face-to-face review sessions and learned to become comfortable talking to industrial staff. Industrial staff also became more comfortable with university students.

The larger question of corporate adoption of analytics in general cannot be credited to the program. While some tools used for pair analysis have become internal standards, there are still a wide variety of opinions on which tools are most effective. Some groups have adopted pair analysis as their preferred analysis method. Others believe subject matter experts should be trained as analysts. And others believe in a service-bureau approach in which problems and data are submitted to a central analysis group.

A much larger effort was needed to generate the widespread, executive-level support to raise the priority of analytics. Although it took over five years, analytics has become a Boeing priority over the last three years. The program did contribute knowledge about the value of analytics.

7. Academic success

In keeping with our HIBAR analysis approach there were three important kinds of results from our Pair Analysis studies: process, content and theory. First, because analysis of video data used psycholinguistics pragmatics methods in a joint activity theory framework, results were of interest to researchers in the field and resulted in publications in cognitive science and psychonomics conferences and journals. Second, the analysis results were useful for Boeing and resulted in changes in product design and training materials. And third, as a new approach to understanding human-information interaction, the work was of interest to visual analytics and human-computer interaction researchers and earned a place in conference publications in BELIV and HICSS. By concentrating on the cognitive task as vocalized by field experiment participants, the university team was able to gain insight into learning processes. In particular, the team observed the SME's growing understanding of visual analysis methods, which can be incorporated into university training programs in data science and analytics.

The university team's use of the HIBAR approach carried substantial risks for graduate student and faculty collaborators. Would it be possible for researchers to build or maintain academic careers through participation in projects that were so closely tied to applications? The university team dealt with these challenges in several ways: First, the team took advantage of application-aware fundamental research publication venues such as the Cognitive Science Society's Trends in Cognitive Science and the Psychonomics Society Cognitive Research Principles and Applications. Technical conferences such as IEEE VIS added application-oriented "paper types" in Calls for Papers, providing another possible venue. The increased interest in methodology papers created a third potential outcome of HIBAR work-not only would the application results and scientific findings be publishable but it also might be possible to publish the research methods used and their methodological grounding in cognitive theory.

Of course the primary role of the university is to provide learning opportunities for students. Building courses and

course sequences from this kind of knowledge-rich application projects holds a great deal of promise. Grounding in applications opens up possibilities for employment of graduates and supports effective curation and validation of academic content. Challenges encountered include lack of commitment to the program by academic units, which typically focus on disciplinary work, difficulties finding willing instructors capable of teaching in a new field without benefit of textbooks etc., and effective outreach to student populations.

8. Lessons Learned

There were a number of lessons learned navigating the corporate maze. Three primary factors drive the adoption of new technology:

- Demonstrated applicability to a company's business problems
- Willingness of the business and technical communities to adopt the technology concept
- Adaptability of corporate infrastructure

In showing applicability to a company's business problems, the Boeing team started engaging both management and the user community early. The strategy was to get problem definitions from multiple groups so a portfolio of successes could be built. This forced the team of computing and analytics researchers to engage with company experts early and often. To insure transparency, the team took care to document all results, even when the results were less-than-satisfactory. Both the user and technical communities attended multiple venues to present project results and benefits of visual and pair analysis. Coverage was broad and included both Boeing-internal and external conferences. Getting the word out led to at least 3 subsequent projects (e.g., commercial airplane market analysis, industrial safety, compute resource usage). Even so, convincing many, especially at the executive level, proved difficult. Executives had multiple reasons that ranged from not wanting to fund another new effort to scepticism about the technology itself to intuition resulting from years of experience. The team continued sending the message (e.g., stressing the value from early analytics projects, the other organizations like GE and DHS using analytics technology, analytics results supplement and do not replace intuition). Eventually analytics became a Boeing corporate strategy.

Many technologies become difficult to deploy because of resistance from the user community, the technical community, or both. The communities introduce problems that effectively block the new technology. For example, user communities become comfortable with certain tools and techniques and resist moving to new tools. Many Boeing analysts are comfortable with Microsoft Excel. The lesson we learned was to find user communities that had outgrown Excel and needed help finding new tools and techniques. Having analysts who could assist through pair analysis available helped greatly.

The Boeing team involved other internal technical communities as soon as the research project started. Technical communities can present a more difficult transition hurdle than business user communities. Business user communities often realize they need help. Technical communities that aren't part of the project team often suffer from both an invented-here (this technology is best because

it was developed inside the group) and a not-invented-here (technology invented by another Boeing group threatens the groups' empire/expertise) syndrome. The initial Boeing visual analytics team was careful to add experts from other Boeing analysis groups (statisticians, text and language analysts). More importantly, visual analytics was positioned to be complementary to (not a replacement for) other analysis techniques.

Often forgotten is understanding that new technology must fit within an existing organizational and environmental/technical infrastructure. Organizations have to figure out how to implement new capabilities, and visual analytics tools were surprisingly acceptable to many groups. More difficult was figuring out how to work the contractual issues (see section 4.1) needed to expand the basic project. The Boeing team addressed the problem through contract extensions that enabled adding directed projects (e.g., industrial safety, aging airplane replacement analysis). After the basic project showed progress, a number of other groups started paying attention and wanted to become the analytics center of expertise. This slowed down approval for subsequent projects and, more importantly, caused conflict among groups who wanted to own the success. It took years of negotiation to resolve the conflicts. Finally, determining how to provision and train analysts proved a long-term challenge. There are both skill and organizational issues to surmount. The initial project team was ill-equipped to handle these problems. Boeing has learned about the problem but does not yet know how to circumvent it. Adding a data scientist job category took over two years. Now data scientist and analyst jobs have become one of the hottest industrial jobs, so competition for talent has become equally heated.

Introducing new technologies often overlooks implementation/deployment needs. Each company has computing delivery system requirements (e.g., how applications work on PCs and/or servers, operating system levels, memory requirements, network performance). The Boeing team involved IT experts as part of the core team. It proved more difficult to add new applications to the approved, company-standard application list. This is important because it's much easier to purchase approved applications. The team had to convince the application standards organization that there were no competitive, already approved applications that would come close. The effort took several years to accomplish and might have been shortened had the team started the approval process earlier. The team did not find a solution to gaining access to data owned by multiple internal organizations. We focused on groups that gave us access to data or worked with publicly available data. The notion of data ownership and protection remains one of analytics outstanding challenges. While not specifically documented, some companies like GE hire dedicated data access and clean up staffs. Other organizations like the U.S. and Canadian governments have had substantial difficulty establishing central data provisioning Web sites (e.g. data.gov). Finally, reports abound about inter-agency difficulties sharing data for medical, police, military, and intelligence operations. See Olson & Downey (2013) and (Gallagher & Heikkila, 2014) for two examples.

From the university research perspective, the project was unique in that it lacked the separation of basic and applied research projects commonly found in traditional academic

research grant programs. This presented the university researchers with the opportunity to develop new HIBAR methods in a well-funded multi-year program. We began by using a set of research methods that had proven successful in the past: social science methods such as grounded theory and cognitive ethnography for observation of the work of expert analysts working with their data, quantitative (i.e. statistical) analysis of controlled laboratory studies of perception of visualizations and interface use by student analysts, and less controlled "crowdsourcing" studies conducted on Mechanical Turk. These studies used displays and tasks that were constructed for the purpose of testing specific factors (e.g., scatterplot distributions (Rensink, 2017)).

As the university team worked with Boeing analysts and technical staff, questions arose about the distinction between observational and experimental research methods. The separation between them generated knowledge that could be more easily attributed to the capabilities and preferences of the peer reviewers for social science versus natural science publication venues than to the most effective way to understand visual analytics. If the team was to develop a sound scientific basis for the design of information systems for visual analysis, members needed to develop methods that were more predictive than social science qualitative methodologies. The university team's pair analysis method came about through a reflective practice (Schoen, 1983) of methodological development. Periodically, the team stepped back and asked what changes might be made to the interface, the task, and the roles played by Subject Matter Experts and Visual Analytics Experts. The team initially followed Clark's (Clark 1996) structured discourse analysis approach closely and adapted it because important aspects of the analytic process were not captured in conventional coding methods. The team found that the framework Clark provided for understanding joint activities was robust and easily accommodated new coding structures. Because pair analysis takes place in a situation that supports some level of control, the research team was also able to make changes in the task and interaction between subject matter expert and visual analytics expert to produce video that would help fine-tune the new coding structures to make some distinctions clearer.

These iterative cycles became what Pickering calls "the dance of resistance and accommodation" (Pickering, 1995). Some were characterized by the discovery of some aspect of the analysis process that resisted the method. When that occurred, the team altered them in such a way as to make that information more available or to focus on aspects that emerged unexpectedly. The team expended more effort developing an ethnography than anticipated and hired a Postdoctoral Research Fellow to help. As the psycholinguistics methods became more complex, a second recent Ph.D. graduate with experience in this method joined the team. The university team did not want its adaptation of existing methods to lack rigor. Therefore, the team collaborated with experts in a given method rather than attempting to learn. This approach proved successful because numerous papers were published and accepted in the content fields.

In addition to supporting methodological depth, these new researchers brought valuable perspectives on the work from their own content areas. The first Postdoctoral RA came from a background in social studies of science and

technology and introduced the team to the field. Perspectives from researchers like Pickering, Latour, Daston and Gallison were helpful in providing examples and perspectives on scientific innovation. As the research team expanded, members were inspired by taxonomies of expertise from (Collins & Evans, 2002).

The final challenge was to find ways to develop these new methods while maintaining scholarly productivity in the form of peer-reviewed publications in academic journals and conferences. These are critical for the success of graduate students and postdocs who hope to find positions in departments that value publications in a specific discipline, such as psychology, social science, or cognitive science. This remains a challenge. There has been progress and new publications (e.g., Topics in Cognitive Science from the Cognitive Science Society, Cognitive Research: Principles and Applications from the Psychonomic Society, and Psychological Science in the Public Interest from the Association for Psychological Science) are appearing. In technical fields, the team has seen an increased interest in work that features team-based interdisciplinary work in venues such as IEEE VIS.

9. Conclusion

The project was a success in a variety of ways. From the industry perspective, Boeing gained millions in offset credits and spread additional funding to Canada and other countries for even more credit. There were less fiduciary benefits as well. The results of the initial pair analytics projects for aviation safety and industrial safety resulted in recommendations that were readily accepted and implemented. The implemented recommendations resulted in direct benefit to the flying public and Boeing manufacturing technicians. Success bred success, and more projects (too many to enumerate) and technical interest resulted. Boeing hired over a dozen new analysts directly and contracted with analytic start-ups. All the direct and start-up staff participated in the program. Finally, the program showed the feasibility of using visual analytics as a new approach to cope with Boeing's ever-expanding data. The success of any one means that the joint program was a clear success.

From the university perspective, the program provided an opportunity to transition to a research approach that integrated basic and responsive research. It will lay the groundwork to use the approach in other application areas. Work in public safety and personalized health have benefitted along with the university's instructional programs in data science, cognitive science, and engineering.

In the larger perspective, the project was exemplary of an approach to research-practice that coordinates the production of scientific knowledge with real-world applications in a well-structured manner. The research approach was carefully designed to find and optimize synergies between situated real-world industry analytics and creation of scientific knowledge of interpersonal communication and coordination of action in graphical visualization environments that are crafted for this purpose. The resulting scientific understanding speaks to expert cognition and collaboration in real-world settings, an area that is challenging to study using other methods.

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