J Intell Manuf (2017) 28:1623–1633
DOI 10.1007/s10845-015-1118-5

Towards a product design assessment of visual analytics in decision support applications: a systematic review

Ovo Adagha[1] · **Richard M. Levy**[1] · **Sheelagh Carpendale**[2]

Received: 19 October 2014 / Accepted: 14 May 2015 / Published online: 30 June 2015

Abstract There is currently an increasing effort to develop visual analytics (VA) tools that can support human analytical reasoning and decision making. In the last decade, advances in this field has allowed the application of various kinds of VA systems in real-world settings. While this represents a promising start from a product design perspective, part of the challenge to the research community is that current VA tools have evolved without due consideration of standardized design criteria and processes. Accordingly, some questions remain to be addressed on what are the useful, underlying attributes of effective VA tools and how their impact can be measured in human-product interaction. These considerations indicate a need to identify a specific range of VA tools and assess their capabilities through state-of-the-art empirical analysis. To address these issues, we conducted a systematic review of 470 VA papers published between 2006 and 2012. We report on the bibliometric techniques, the evaluation attributes and the metrics that were used to sample and analyze the body of literature. The analysis focused mainly on 26 papers that implemented visual analytics decision support tools. The results are presented in the form of six inductively derived design recommendations that, when taken together, uniquely contribute to the fields of product design and visual analytics.

Keywords Visual analytics · Decision support · Product design · User experience · Design evaluation · Product development

Introduction

We currently witness a growing interest of product design research in the field of visual analytics. Defined as the science of analytical reasoning facilitated by interactive visual inter-faces (Thomas and Cook 2006), visual analytics tools have been heralded as technology products that can synthesize information from complex and dynamic data and in ways that directly support assessment, planning, and decision making. The earliest work relating to real world application of visual analytics can be linked to Bilgic (2006) and Chen et al. (2006). Recent advances, for example (Andrienko et al. 2007; Booshehrian et al. 2012; Reddy et al. 2012; Rudolph et al. 2009; Savikhin et al. 2011), show that application of VA tools can facilitate decision making in real-world settings.

While a broad range of VA tools exists, evidence regarding their effectiveness, and experience of use, is rather limited. This has stimulated a shift of focus from the extent and manner in which visual analytics can be applied in real-world settings, to understanding the design process and the underlying attributes of effective visual analytics, and how the quality of the product experience is evaluated through the use of performance metrics.

Alben (1996) defined the human-product interaction "experience" to include all the aspects of how people use

---

✉ Ovo Adagha
osadagha@ucalgary.ca

Richard M. Levy
rmlevy@ucalgary.ca

Sheelagh Carpendale
sheelagh@ucalgary.ca

[1] Computational Media Design Program, Faculty of Environmental Design, University of Calgary, Calgary, AB T2N 1N4, Canada

[2] Department of Computer Sciences, University of Calgary, Calgary, AB T2N 1N4, Canada

an interactive product: the way it feels in their hands, how well they understand how it works, how they feel about it while they are using it, how well it serves their purposes, and how well it fits into the entire context in which they are using it. If these experiences are successful and engaging, then the tools become valuable to users and noteworthy of the design and evaluation process from which they emerged.

Although considerable research has focused on the design and evaluation of VA tools (Chinchor et al. 2012; Jeong et al. 2008; Kang and Stasko 2012; Kluse et al. 2012; Konecni et al. 2010; Plaisant et al. 2008), the outcome is a research agenda characterized by a horde of experiential concepts that, to some extent, differ in terms of theoretical backgrounds, research directions, and design processes.

From a product design perspective, design evaluation requires the consideration of several performance attributes rather than common usability metrics (Liu et al. 2011). These factors clearly illustrate the need to develop a general framework that can facilitate the design and evaluation of VA tools. With qualitative and quantifiable measures, researchers can adequately evaluate a product's capabilities in relation to its use (Burnell et al. 1991). Hassenzahl and Tractinsky (2006) argue that such assessments have an impact on future user experiences. Moreover, they form a basis for the research community to streamline the design process in a manner that reflects the goal of enhancing user experience.

These considerations motivated us to articulate a framework that can be used for design and evaluation of VA tools. Using the evaluation metrics proposed by Scholtz (2006a) and Wang et al. (2011) as *a priori* framework, we conducted a systematic review that seeks to evaluate, synthesize, and present the empirical findings in visual analytics literature from 2006 to 2012. The review focuses mainly on papers that developed visual analytics decision support tools (VADS), and provide an overview of application areas, their attributes, and design implications for research and product development.

In doing so, we hope to uncover findings that can be extrapolated broadly to contribute to a common understanding of approaches and practical guidance for designing VA tools.

The paper is organized as follows: In "Background" section, we provide a discussion of user experience evaluation as a feature of product design in visual analytics. "Methods" section describes the methods and the theoretical roots taken to derive the evaluation framework used for this review. "Results" section reports the findings of the review. "Discussion" section discusses the findings in the form of seven inductively derived recommendations. "Limitations" and "Future work" sections reports on the limitations, contributions, and concludes with recommendations for further research.

Background

User experience in the product development context

The discussion of user experience in product design research draws on some interesting insights. Hassenzahl (2005) suggests that a product, into which we classify visual analytics systems, has certain attributes which can be combined to convey a peculiar character. In order to trigger an experience of a product, a designer has to manipulate these attributes to give access to utility and usability. The same can also apply to the overall quality of a product which, as articulated by Hassenzahl and Tractinsky (2006), often depends on how well the attributes are linked with users' needs. Clearly, these reflections highlight the complex and layered nature of product experience, and point to a need to use certain attributes to design products that can be effective and useful.

User experience metrics for visual analytic tools

Researchers have long argued that usability metrics are inadequate for evaluating the effectiveness of intelligent technologies such as visual analytics tools (Despont-Gros et al. 2005; MacDonald 2012; Scholtz 2006b; Tintarev and Masthoff 2012). Scholtz (2006a) and Wang et al. (2011) proposed an evaluation framework for visual analytics tools that goes beyond standard usability metrics. The framework proposed by the authors includes focusing on performance attributes such as situation awareness, collaboration, interaction, creativity, and utility. Within this framework, they recommended specific metrics to provide designers with measures to track how the design components support the user experience. According to Tullis and Albert (2008), user experience metrics, that are based on a reliable system of measurement, can add structure to the design and evaluation process, give insight into the findings, and provide value to users. In other words, the user experience metrics can help identify "good" VA tools from "not so good" VA tools by showing, for instance, if a analyst's experience on using VA tool is improved or not.

With these considerations in mind, our research questions for this study are then as follows:

1. What is the nature of visual analytics product application in decision support settings?
2. What attributes and metrics are needed to enhance the human-product interaction experience in visual analytics decision support tools?

Methods

Guided by the established method of systematic review (Higgins and Green 2008), we undertook the review in six distinct stages: a search for relevant papers, development of a coding protocol, identifying the inclusion and exclusion criteria, data extraction, critical analysis of data, and synthesis of findings. In this section, we describe the methods used.

Data sources

The review spans the period from 2006 to 2012, following the peer-reviewed papers published since *Illuminating the Path* (Thomas and Cook 2005). Specifically, we obtained the initial set of papers from the electronic databases of journals and conference proceedings that are known to publish VA papers, namely: VAST, Information Visualization EUROVA, Pacific Viz, and IEEE Lecture notes in Visual analytics.

This was followed by a manual search of online search engines for additional VA papers published in other journals and conferences. This procedure yielded a total dataset of 470 VA publications. The list is not exhaustive, but the major VA research strands are represented. We then organized and indexed the papers for sampling.

Inclusion and exclusion criteria

We chose decision support in visual analytics because it provides a concrete application sample for the analytic experience. We also considered it important to define the selection criteria for our final sample, because we wanted to reduce the possibility of selection bias. The final sample was selected using the following criteria:

- Papers must be published in a peer-reviewed journal or conference proceedings;
- Papers must be full papers with empirical evidence (contest papers, workshop briefs, panel sessions, posters, and short papers were excluded);
- Papers must implement a VA technology for decision support in a real-world setting.

To this end, we performed a manual check on the abstracts of the 470 papers using the inclusion criteria. In addition, we read the text of each paper to verify its ‘decision support’ content. Most of the VA papers identified in the initial search, that clearly did not meet the criteria, were omitted from further consideration. Following this procedure, we collated a final sample of 26 papers which we found to be of acceptable rigour, credibility, and relevance (Table 2).

Coding protocol

We developed a coding protocol using the Cochrane Handbook style for Systematic Reviews of Intervention (Higgins and Green 2008) and the content analysis technique of a priori coding (Stemler 2001). The coding protocol was mostly influenced by the evaluation framework proposed by Scholtz (2006a), and Wang et al. (2011). From their work, we developed six high level attributes: Situation awareness, Collaboration, Interaction, Creativity, Utility and User-oriented design. All six attributes are distinguished in having their own underlying metrics, which we adapted as coding units in the protocol. We describe the attributes and coding units below.

Situation awareness

Situation awareness (SA) is a cognitive process in decision making and is defined as ‘the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future’ (Endsley 1995).

According to the visual analytics research agenda (Thomas and Cook 2006), the analytical process involves similar tasks such as: understanding historical and current situations, as well as the events leading to current conditions; identifying possible alternative future scenarios; determining indicators of the intent of an action; and supporting the decision maker in times of crisis. VADS tools that do not support situation awareness tend to allow information overload or inadequate information to affect decision making.

For this attribute, we wanted to measure how situation awareness is incorporated in the design of VADS tools. We developed the coding units according to the three layers of Endsley’s situation awareness model, which are: perception, comprehension, and projection (Endsley 1995). For the perception layer, we reviewed the papers to determine the extent to which the VA decision support tools show a demonstrated ability to track the changes of information when operated by the users in field trials. For the comprehension layer, we assessed the application of VA decision support decision support tools in providing contextual analysis of environments to users. For the projection layer, we searched the literature for test reports on the aptitude of VADS to support future scenario projections. And finally, we wanted to understand how many of the tools were reported to have a combination of the three afore-mentioned layers.

Collaboration

The ability to share data while using different views is a necessary feature of visual analytics systems that are designed for collaboration (Scholtz 2006a). Analysis of this attribute was guided by the need to review the effectiveness of VA decision support systems, as reported in the literature, when facilitating communication and information sharing between users. For this purpose, we iteratively developed the following coding units: ability to share evidence; supports intuitive communication; can allow multiple, coordinated views;

can track information flows; and combination of all four metrics.

Interaction

Assessment of this attribute was based, in part, on the ISO 9241-110 principles of human-system interaction (ISO 9241–110 2006). We consider this interaction as a form of "dialogue" between the human component and the VA system. We examined the papers in respect to whether, and to what extent, the VA decision support tools were able to support interaction with users. To this end, we coded the data using the following units: suitability for the task; controllability; self-descriptiveness; support customization of information; enable access to information; and combination of all five metrics.

Creativity

Lubart and Georgsdottir (2004) defined the concept of creativity as the ability to produce work that is high in quality and appropriate (i.e., solves problems, useful for certain tasks). We share this view of creativity because it suggests that creativity can occur in complex domains where decisions are made. This implies that support for creativity should take into account the environment that supports decision making. As such, VADS tools that support creativity should be able to enhance the creative experience of the user(s), therefore improving the analytical processes and outcomes. To evaluate this attribute, we reviewed the literature using the following metrics as coding units: support individual tasks; effective in searching for analytical results; ability to show high quality of analytic solutions; user satisfaction with solutions; and combination of all four metrics.

Utility

According to Scholtz (2006a), the utility of the VA system is one of the most important metrics of measuring its effectiveness from the user perspective. We developed the coding units based on Davis's technology acceptance models (TAM) (Davis 1985), which examines psychometric properties of the systems' characteristics as perceived by the users.

In essence, the environment should allow the user to spend more time on task and less time on the system being used. Compatibility with the context of use, perceived ease of use, perceived usefulness, increased effectiveness on the task, and less aggregate time expended in finding analytical solutions, are factors that can be associated with the utility attribute of visual analytic decision support tools. We evaluated the utility attribute using the afore-mentioned metrics as coding units.

User-oriented design

The coding scheme we developed for this attribute was based on the visual analytics research agenda put forward by Thomas and Cook (Thomas and Cook 2006). In formulating the coding units, we sought to measure the extent to which designers of VA decision support tools focus on the intended users, real data sets, and real tasks. We also wanted to understand how the user requirements are defined in the design and development life cycle of VADS. In the light of these considerations, we developed the following coding units: analysis of user and context requirements; active involvement of intended users; iteration of usability design; evaluation with intended users; multi-disciplinary design input; use of real-world data; and combination of all units.

Procedure

First, we tested the coding protocol on a random selection of five papers from the sample dataset. Two independent raters—two PhD students in computer sciences—joined us in this process. At the end of this phase, we modified some coding units to account for discrepancies in the protocol.

We then coded the sample dataset independently and discussed the results during intensive team meeting sessions, over a period of eight months. These discussions provided a platform for validity checks, consistency in the coding, resolving disagreements, and strengthening the intracoder and intercoder reliability. The time taken to code each article varied considerably, ranging from over four hours to an hour. To maintain consistency, we re-read the papers on which the coding protocol was based. Using Cohen's Kappa (Cohen 1960), we calculated the inter-rater reliability to be 0.64, which can be considered a "substantial agreement". Further, we discussed our preliminary findings with colleagues who also conduct research in information visualization and visual analytics. At the end of this procedure, we resolved all disagreements and analyzed the data.

Results

Overview of VA publications and application areas

Table 1 shows the distribution of the papers by journal and conference proceedings from the search results. The substantial number of identified papers (n = 470) suggests that visual analytics is a rapidly growing research field. Overall, we found that 5.5 % of VA papers published between 2006 and 2012 developed decision support applications for real-world problems. This suggests that limited research work has been done in terms of the design and application of VADS to real world decision support problems.

Table 1 Overview of VA publications (2006–2012)

Journal	Year	VA papers (2006–2012)	VADS papers (2006–2012)	%
VAST	2012	62	–	–
VAST	2011	57	3	5.3
VAST	2010	58	1	1.7
VAST	2009	56	5	8.9
VAST	2008	46	2	4.3
VAST	2007	46	5	10.9
VAST	2006	23	3	13.0
EURO VA	2012	7	1	14.3
EURO VA	2011	10	–	–
EURO VA	2010	10	–	–
Others	2006–2012	88	6	6.8
Total		470	26	5.5

Further analysis was based on the final sample of 26 papers. This sample reflects the 22 different applications of visual analytics for decision support in real world settings (see Table 2).

Given the data in Table 2, we can infer that most of the application areas have spatial and temporal aspects; and often involved stakeholders in the time-critical decision making processes. The data shows that the diversity of applications areas correlates with the research agenda for visual analytics. However, it also reinforces the need to develop more applications for decision support in other real-life scenarios where complex information has to be processed and analyzed.

Table 3 shows the attributes of VADS in the reviewed papers as reported by the coding protocol. Each code refers to frequency and percentage values of the coding units as identified in the data.

Situation awareness

We observed that perception (i.e., ability to track the changes of information—36.5 %) and comprehension (ability to provide environment for contextual analysis—48.1 %) were predominant features in the final sample of papers we reviewed. However, we found few examples (7.7 %) where situation awareness was linked to the ability of the systems to support users in making future scenario projections. The assessments also indicate that the three levels were fully integrated in about 7.7 % of the sample papers.

Additionally, we found several examples where references were made on the capability of the VADS tools to support situation awareness. For example, some of the references read as follows:

Table 2 VA decision support applications (2006–2012)

	Real world applications ($n = 22$)	Papers ($n = 26$)
1.	Evacuation scheduling	(Andrienko et al. 2007)
2.	Epidemic modeling and response evaluation	(Afzal et al. 2011)
3.	Situation awareness in astrophysics	(Aragon et al. 2008),
4.	Entity resolution in social networks	(Bilgic 2006),
5.	Fisheries management	(Booshehrian et al. 2012)
6.	Financial transactions	(Chang et al. 2007) (Rudolph et al. 2009)
7.	Semantic analysis	(Crossno et al. 2009)
8.	Journalistic inquiry	(Diakopoulos et al. 2010),
9.	Broadcast news video exploration	(Luo and Ghoniem 2007; Luo 2006)
10.	Linear trend discovery in datasets	(Guo et al. 2009; Shrinivasan et al. 2009)
11.	Pandemic decision support	(Guo 2007)
12.	Emergency response	(Kim et al. 2007; Maciejewski et al. 2008)
13.	GeoTwitter analytics	(MacEachren et al. 2011)
14.	Understanding spatiotemporal hotspots	(Maciejewski et al. 2010)
15.	Animal-human health	(Maciejewski et al. 2007)
16.	Maritime risk assessment	(Malik et al. 2011)
17.	Clinical decision support in psychiatry	(Mane et al. 2012)
18.	Economic decision-making	(Savikhin et al. 2008)
19.	Airlift decision making	(Soban et al. 2011)
20.	Micro grid energy mix planning	(Stoffel et al. 2012)
21.	Radio frequency localization	(Han et al. 2009)
22.	Hotel visitation analysis	(Weaver et al. 2007)

Table 3 Frequency distribution of attributes reported in VADS tools (2006–2012)

Attribute	Coding references *n (%)*
Situation awareness ($N = 52$)	
Can track changes in information	19 (36.5)
Can provide environment for contextual analysis	25 (48.1)
Can support future scenario projections	4 (7.7)
Combination of all	4 (7.7)
Collaboration ($N = 63$)	
Ability to share evidence	3 (4.7)
Can support intuitive communication	12 (19.1)
Can allow multiple, coordinated views	36 (57.1)
Can track information flows	12 (19.1)
Combination of all	0 (0)
Interaction ($N = 124$)	
Suitability for the task	12 (9.7)
Controllability	39 (31.5)
Self-descriptiveness	12 (9.7)
Support customization of information	35 (28.2)
Enable access to information	21 (16.9)
Combination of all	5 (4.0)
Creativity ($N = 137$)	
Support individual tasks	11 (8.0)
Effective in searching analytical results	58 (42.3)
Ability to show high quality of analytic	46 (33.6)
solutions User satisfaction with solutions	13 (9.5)
Combination of all	9 (6.6)
Utility ($N = 51$)	
Perceived ease of use	4 (7.8)
Compatible with the context of use	14 (27.5)
Perceived usefulness	11 (21.6)
Enhances effectiveness on the task	10 (19.6)
Reduction in time	4 (7.8)
Combination of all	8 (15.7)
User-oriented design ($N = 175$)	
Analysis of user and context of use	80 (45.7)
Active involvement of intended users	22 (12.6)
Iterative design	17 (9.7)
Evaluation with intended users	17 (9.7)
Multidisciplinary design input	7 (4)
Use of real world data	32 (18.3)
Combination of all	0 (0)

> *… The planner should also be able to spot and explore rationality problems when time permits but immediate detection is not so much required…*
> *… the planner should involve his/her background knowledge and/or additional information to assess the feasibility of this plan…*
> *… as the user inserts decisions points, scrolls through time, and revisits other scenarios, these interactions are tracked and displayed in the decision history view...*

Further, there were instances where the SA attribute was clearly demonstrated in the papers, notably:

> *…the visual framework allowed managers to ask new questions, promoted discussion and debate, and built trust between managers and scientists for the data analysis process…*
> *… He (the analyst) observed that the system's ability to process large datasets allows him to quickly filter the data into manageable subsets while providing interactive spatiotemporal displays that further aid him in making a decision using the best information available…*

From the references, it can be seen that situation awareness is a factor in the design of VADS tools. It gives an indication of how the VADS systems are designed to incorporate the user's background perceptual knowledge when performing analytical tasks; how their comprehension of the situation was improved following interaction with the VA tool; and, consequently, the level of future projections derived by the users.

Collaboration

The data indicate that 57.1 % of VADS tools can allow multiple, coordinated views. In facilitating intuitive communication, we observed that the incorporation of contextual data and domain knowledge in VADS tools made it easier access information (19.1 %). We also recorded 19.1 % codes where the capability of VADS tools to track the flow of information was demonstrated. This suggests a link between the capability of existing VADS tools to actively track the visual changes in a system and allowing users to explore the visual representations interactively. For example, one document expressed, '*These different modes enable multipurpose use of the display. One of the purposes is detection of potential feasibility problems due to simultaneous arrival of multiple vehicles to the same place.*'

Relatedly, an interesting aspect of the data was the low frequency we recorded for the VA systems' ability to facilitate evidence-sharing among collaborators. We also observed that there was hardly any paper that reported all the metrics we coded for this attribute.

Interaction

Table 3 shows the distribution of the codes for Interaction. Roughly two-thirds of the codes were more or less direct references to *Controllability* and *Customization of information*.

Based on this evidence, we can deduce that technical functionality and visual elements were a central consideration in the VADS design process.

The other 4 coding units reported low frequencies (the exception was ‘access to information’, which had 16.9 %). This suggests that information used for analysis and decision making was usually explored at various levels of detail. When we reviewed the papers in terms of *Suitability for the task* and *Self-descriptiveness*, we found a striking similarity in frequency (9.7 %). According to ISO 9241-110, self-descriptiveness relates to system consistency, quick comprehension, and clarity of possible actions from the user perspective. On the other hand, interaction enhances a tool’s suitability for a task if the user can efficiently complete a task. From the foregoing, we can infer that the extent to which *self-descriptiveness* is incorporated in a VADS tool appears to have a direct correlation on its *suitability for the task*—at least when viewed in the context of the tool’s interaction capabilities. We interpreted this to mean that self-descriptive interactions in VA systems are more likely to support users in carrying out their tasks effectively.

Creativity

With respect to creativity, the results indicate that most of the VADS tools in the papers we reviewed were considered to be effective in representing high quality of analytical outcomes on the visual interfaces. Further, the coded references appear to show a trend of user satisfaction with solutions and the extent to which the VADS were able to support individual tasks. A possible reason for this may be that evaluation experiments were actually tested for this feature, and so the user’s comments were often recorded. The relevance of creativity on the user satisfaction can be measured with the frequency we recorded (9.5 and 6.6 % respectively). Table 3 illustrates this further.

We also found some references in which users reported their creative experiences with VADS tools:

> *User comments indicated that data-taking facilitated decision-making.*
> *…the planner concludes that the capacities in the destination places are not optimally used.*
> *The response of these policymakers was highly positive, verifying that the goal of facilitating communication … was well achieved.*

Utility

Table 3 displays the results for the attributes pertaining to Utility. Overall, 27.5 % codes we measured for this attribute were in the *context of use*. We surmise that this relates to the level of inquiry into the user requirements by VA researchers—that is, the degree to which they ensure the tools are applicable to the context.

The results also highlight favourable numbers for *Perceived usefulness*, which, as defined by Davis (1989), is the degree to which a person believes that using a particular system would enhance their performance on a task. Interestingly, the systems are reported to *enhance effectiveness on the task*, showing a strong co-relation with *Perceived Usefulness*. The results tend to support the view that the two attributes are interdependent.

We also found a strong correlation between *perceived ease of use* and *time expended* in finding analytical solutions, judging from the exact frequencies of the codes. We deduce that *Perceived ease-of-use* of VADS tools may be a significant determinant of the amount of time spent on finding analytical solutions. The evidence also suggests that the amount of time gained by the use of VADS tools is not being tracked in evaluation experiments.

Regarding the extent to which the VA applications incorporated all these coding units, the data show a statistically significant trend, which suggests that some of the papers attempted to elicit information from the users on how their experiences had been impacted by interaction with the VADS tools. Specifically, the users commented on the adequacy of the designs to their work tasks, thereby increasing their ability to make informed decisions. However, these were found in only about one third of the sample papers reviewed.

User-oriented design

We found many references of user-oriented design in the sample papers. This appears to support the view that most VADS researchers collaborate with users at some point in the design process (Damodaran 1996). The difference between the various approaches, we observed, is the degree of user influence in the design process. In this case, the degree of user influence was informed by both the type and depth of user participation.

The distribution in Table 3 indicates that the context of use and users’ decision support needs were explored and analysed in detail by VA researchers prior to the tool design. This trend was consistent in all the papers we reviewed. One interpretation is that VADS largely involve the application of technology to novel decision-making tasks that have not been researched by other disciplines.

Further analysis of the references indicates that only 12.6 % of the papers reflect an active involvement of users in the design processes. We believe that this phenomenon highlights a growing need in the development of VA decision support tools that are designed for real world applications. The reason is that many real-world decisions, even when they seem to focus on technical issues, are in fact socio-technical in nature (Damodaran 1996), thus requiring a more active involvement of the users to provide specifications in the design process.

A noteworthy feature in the chart is the similarity in the results we recorded for *Iterative Design and Evaluation* with intended users. We observed that the process of evaluation, in which changes and refinements are made, did not often involve users. Remarkably, this trend was reported in only about 9.7 % of the papers. For a process that is intended to improve the usability and effectiveness of a design, the implication is that the current distribution may not sufficient.

According to Thomas and Cook (2005), to build an effective VADS requires collaboration from multiple disciplines. Thus, it can be argued that inadequate collaborative participation in the design of VA systems makes the process time-consuming and error-prone. The results also show that multidisciplinary design input needs to be emphasized in the design VADS tools. This suggests a gap between researchers, programmers, designers and users, in contrast to the guidelines proposed in the VA research agenda.

We also observed that only 18.3 % of papers reported the use of real-world data in VADS. This may imply that majority of the papers use simulated datasets to design the systems. This underlines the key issue of product validity and credibility in VA decision support tools.

Discussion

There are several possible ways of looking at these findings, but we will focus only on six aspects in this discussion. The recommendations, as stated below, are not prescriptive. Rather, they reflect suggestions to help improve the product design approach of VA tools, specifically VADS tools.

First, the results imply a limited emphasis on the incorporation of *Situation Awareness* as a key attribute in the design of VA decision support tools. The application of visual analytics to decision support requires a much more advanced level of situation understanding and accurate projection of future events in view of the user's analytic tasks. With such tasks, the user is uncertain about the nature of the problem, the alternative solutions or value for making a choice (Alavi and Napier 1984). It may be useful if future VADS are designed to adequately support the users overall awareness of issues when evaluating complex information. Situation awareness forms the critical input to an individual's decision making, and is often the basis for all subsequent actions (Endsley 1988). Therefore, we recommend that VA decision support systems should be designed to facilitate the continuous acquirement of Situation Awareness, by providing solutions to domain-specific and time-critical problems. Design techniques should be developed to enhance situation awareness, and, to objectively assess the effect of the VADS tool on a user's situation awareness.

The ability to support evidence-sharing, synchronously and asynchronously, among collaborative users, in a VA system is important. While we gained further understanding on the trend of *Collaboration* in VA literature, we found that no single study incorporated all the units we used in measuring the attribute. A possible reason is that typical design processes reflect a focus on the ability of the VADS technology to capture and track the steps taken by the users in the process of decision making. This attribute is useful in the analysis process, but often, as the results show, not enough to support evidence-sharing among collaborative users of the VADS tool. The data provide ample justification to support this view. To facilitate effective communication and information sharing between collaborators, we recommend that VA decision support tools should purposively incorporate all the attributes that support seamless collaboration between users. At a minimum, VADS tools should demonstrate the capability:

1. To share data between users;
2. To support intuitive communication;
3. To support multiple, linked displays that would allow different users to assess different data;
4. To track information flows between users.

We recommend that these attributes should be targeted in the design and evaluation stages of VA decision support tools.

We can look at *Interaction* as a communication process between the user and the system (Bennett 1976). In a successful interaction process the user interacts automatically with the system while concentrating on the analysis at hand. What we infer from the results is the tendency of interaction dialog in existing VADS tools to be geared towards *controllability* and *customization*. While the data indicate that interaction dialogs allows users sufficient access to information, the evidence tend to suggest a trend in which the dialogs were often less comprehensible to the users in ways that made VA tools rather unsuitable for the analytic tasks. This is perhaps a clear indication of what Green et al. (2011) refers to as the general disposition to create interfaces based on their own methodologies and interaction metaphors. Clearly, this mismatch underlines the need for interaction design techniques that are user-adapted and context-oriented. This type of design requires a focus on the *outcomes* of the interaction rather than the *process* of interaction. We propose an adaptive model in which components such as, the context of use, the user, the VA system, and the designer combine to establish products and outcomes that respond adequately to the six attributes we used in measuring interaction.

As noted earlier, *Creativity* may be stimulated or hindered depending on the nature of the environment in which a task is performed. The relative frequency we observed in the literature may be a reflection of how visual analytics enables user creativity in multiple domains. At these levels, one can assume that current VA tools can support faster and more accurate decision making. Therefore, more work needs to done to stimulate creativity. Thus, a VADS environment should allow for elements that are inclined to support the user's creative needs. In addition, we recommend that VADS tools should be designed in such a way that the interface can act as a vehicle of creativity and self-expression for the decision maker.

The purpose of most decision support tools is to support the user in arriving at a decision through analysis. For VADS tools, we associate this goal with the notion of *Utility*, which can be measured through feedback from the user. The results show a tendency of VADS tools' designers to take the contextual aspects into consideration. However, this development does not always translate to ease of use and less time spent on tasks. The evidence presented in Table 3 suggests that the relationships between the *Utility* attributes are similar. Specifically, one can see that *ease of use* influences the amount of *time spent on task*. The findings have implications on user acceptance. Rather than focusing only on usability issues, we suggest that designers should also evaluate and adapt the systems for usefulness, timeliness, and ease of use.

With respect to *User-oriented design*, our findings identified a typical approach in VADS tools, which is—build a prototype, test with intended users, measure usability criteria, and iteratively refine design. However, in a user-oriented approach, it is important to determine the user and context requirements prior to design. In addition, seeking multidisciplinary input in the implementation stages could allow higher levels of adoption by users. Also from the sample papers, we deduced that the data used in the design process were mostly simulated data, and therefore may not portray an accurate dynamics of decision problems that require the use of VA tools. This calls for the use of real datasets in the design and development cycle.

Limitations

Some limitations may have affected the data collection and interpretation of results in this review. First, due to the diverse publication venues available to VA researchers, extracting all the papers in the field would have been difficult. There is also a risk that relevant papers may have been omitted due to our choice of keywords and search strings. However, we are confident that the initial dataset of 470 papers sufficiently represents the major VA publications from 2006 to 2012, and that this number is large enough to support the validity of our conclusions.

Second, we appreciate that systematic literature reviews and content analysis methodologies are mostly subjective. However, the rigor of the coding technique used and the research experience of the researchers ensured that the data analysis was fairly reliable. We believe that other researchers using the same coding protocol would produce similar results.

We acknowledge that difficulties arise when attempting to investigate textual data for 'state-of-the art trends'. We are aware that generalizability of these analyses is limited by the focal sample employed for the study. In this paper, we analysed only 26 papers that are specific to decision support. This, in itself, sheds a limited light into the published literature.

The metrics we adapted into coding units were considered with great attention to allow, as much as possible, an accurate analysis of the data. The models and literature we used to support the metrics were selected based on our research questions and objectives. Nevertheless, we acknowledge that there may be other models and metrics out there. It is not our intention to present the framework we used as a well-specified theory. Rather, we invite further research, using other models and attributes.

The content analysis approach posed some methodological challenges: the selection procedure for including the papers was somewhat subjective; also, due to the extensive logistics and time constraints, we could not extend the inter-rater and intra-rater agreement to include more researchers. In future reviews, it may be beneficial to expand the number of researchers working on the coding procedure, which may in turn increase the reliability of inferences made from the data.

Finally, in the course of conducting this research, we have developed a deeper appreciation of the passion, commitment, creativity, and rigor brought to the field of visual analytics by the thousands of dedicated researchers. We recognize the diversity of perspectives on visual analytics and related research. For these reasons, we do not suggest that the findings are indicative of the general trends in the field, but rather some trends that reflect our specific research questions, methodological assumptions, and research interests.

Future work

So far, the design attributes and metrics proposed here have not been tested in real world settings with visual analytics tools. We will continue to refine these attributes through additional projects and to apply them to the design evaluation of a VA decision support tool with stakeholders in a real world domain.

Conclusion

This paper reviewed the most exciting aspects of product design and development in the field of visual analytics. In this paper, we provided a rich description of an evaluation framework that is, in part, already studied in visual analytics research, but not well considered in the design and evaluation of visual analytics tools. To our knowledge, this is the first comprehensive review to address the benefits of integrating VA tools in product design. The results indicated a general consensus that visual analytics tools have the potential to support analytical reasoning in many fields of human endeavour. It also provided preliminary data to better understand the reach and capabilities of visual analytics decision support tools in real-world applications.

The results have several implications for designers of VA tools: first, the findings answer the question "What attributes and metrics are needed to enhance the human-product interaction experience in visual analytics decision support tools?" This is one of the primary contributions from this study. Further, the findings suggests that using the attributes and metrics identified in this study could result in comparable outcomes in the design and evaluation of VA tools.

Third, while the design evaluation approach demonstrated here is specific to visual analytics, the user experience attributes and metrics we described can be adapted to any type of product design and any type of technology. This is one of the contributions from this study.

In conclusion, the findings gave rise to new design recommendations for VA decision support tools. These design recommendations were constructed from the analysis of the data sample. We expect that the proposed design recommendations will uniquely contribute to the fields of visual analytics, product design and user experience design.

Acknowledgements The work in this paper was supported by the Computational Media Design program (CMD), the InnoVis Group in Interactions Lab, Faculty of Environmental Design (EVDS) at the University of Calgary, NSERC, SMART Technologies, AITF, Surfnet, and GRAND NCE. We would like to thank the journal editors and the anonymous reviewers for their helpful suggestions.

References

Afzal, S., Maciejewski, R., & Ebert, D. S. (2011). Visual analytics decision support environment for epidemic modeling and response evaluation. In *2011 IEEE conference on visual analytics science and technology (VAST)* (pp. 191–200).

Alavi, M., & Napier, H. A. (1984). An experiment in applying the adaptive design approach to DSS development. *Information and Management*, *7*(1), 21–28.

Alben, L. (1996). Quality of experience. *Interactions*, *3*(3), 11–15.

Andrienko, G., Andrienko, N., & Bartling, U. (2007). Visual analytics approach to user-controlled evacuation scheduling. In *IEEE symposium on visual analytics science and technology* (pp. 43–50).

Aragon, C. R., Aldering, G. S., & Thomas, R. C. (2008). Using visual analytics to maintain situation awareness in astrophysics. In *IEEE symposium on visual analytics science and technology* (pp. 27–34).

Bennett, J. L. (1976). User-oriented graphics systems for decision support in unstructured tasks. In *Proceedings of the ACM/SIGGRAPH workshop on user-oriented design of interactive graphics systems*.

Bilgic, M. (2006). D-dupe: An interactive tool for entity resolution in social networks. In *IEEE symposium on visual analytics science and technology* (pp. 43–50).

Booshehrian, M., Möller, T., Peterman, R. M., & Munzner, T. (2012). Vismon: Facilitating analysis of trade-offs, uncertainty, and sensitivity in fisheries management decision making. *Computer Graphics Forum*, *31*(3), 1235–1244.

Burnell, L., Priest, J., & Briggs, K. (1991). An intelligent decision theoretic approach to producibility optimization in conceptual design. *Journal of Intelligent Manufacturing*, *2*(3), 189–196.

Chang, R., Ghoniem, M., Kosara, R., Ribarsky, W., Yamg, Y., Suma, E., et al. (2007). WireVis: Visualization of categorical, time-varying data from financial transactions. In *IEEE symposium on visual analytics science and technology* (pp. 155–162).

Chen, C., Ibekwe-sanjuan, F., Sanjuan, E., & Weaver, C. (2006). Visual analysis of conflicting opinions. In *IEEE symposium on visual analytics science and technology.*

Chinchor, N., Cook, K., & Scholtz, J. (2012). Building adoption of visual analytics software. In J. Dill, R. Earnshaw, D. Kasik, J. Vince, & P. C. Wong (Eds.), *Expanding the frontiers of visual analytics and visualization* (pp. 509–530). London: Springer.

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*, *20*, 37–46.

Crossno, P. J., Dunlavy, D. M., & Shead, T. M. (2009). LSAView: A tool for visual exploration of latent semantic modeling. In *2009 IEEE symposium on visual analytics science and technology* (pp. 83–90). IEEE.

Damodaran, L. (1996). User involvement in the systems design process—a practical guide for users. *Behaviour and Information Technology*, *15*(6), 363–377.

Davis, F. (1985). *A technology acceptance model for empirically testing new end-user information systems: Theory and results.* Doctoral dissertation, Massachusetts Institute of Technology.

Davis, F. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, *13*(3), 319–340.

Despont-Gros, C., Mueller, H., & Lovis, C. (2005). Evaluating user interactions with clinical information systems: A model based on human-computer interaction models. *Journal of Biomedical Informatics*, *38*, 244–255.

Diakopoulos, N., Naaman, M., & Kivran-swaine, F. (2010). Diamonds in the rough: Social media visual analytics for journalistic inquiry. In *IEEE symposium on visual analytics science and technology* (pp. 115–122).

Endsley, M. R. (1988). Design and evaluation for situation awareness enhancement. In *Proceedings of the human factors and ergonomics society annual meeting* (pp. 97–101).

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *37*(1), 32–64.

Green, T. M., Wakkary, R., & Arias-hernández, R. (2011). Expanding the scope: Interaction design perspectives for visual analytics. In *44th Hawaii international conference on system sciences* (pp. 1–10).

Guo, D. (2007). Visual analytics of spatial interaction patterns for pandemic decision support. *International Journal of Geographical Information Science*, *21*(8), 859–877.

Guo, Z., Ward, M. O., & Rundensteiner, E. a. (2009). Model space visualization for multivariate linear trend discovery. In *2009 IEEE symposium on visual analytics science and technology* (pp. 75–82). IEEE.

Han, Y., Stuntebeck, E. P., Stasko, J. T., & Abowd, G. D. (2009). A visual analytics system for radio frequency fingerprinting-based localization. In *2009 IEEE symposium on visual analytics science and technology* (pp. 35–42). IEEE.

Hassenzahl, M. (2005). The thing and I: Understanding the relationship between user and product. *Funology, 3*, 31–42.

Hassenzahl, M., & Tractinsky, N. (2006). User experience—a research agenda. *Behaviour and Information Technology, 25*, 91–97.

Higgins, J. P., & Green, S. (2008). *Cochrane handbook for systematic reviews of interventions: Cochrane book series.*

ISO 9241–110. (2006). *Ergonomics of Human System Interaction.*

Jeong, D. H., Dou, W., Lipford, H. R., Stukes, F., Chang, R., & Ribarsky, W. (2008). Evaluating the relationship between user interaction and financial visual analysis. In *Visual analytics science and technology* (pp. 83–90).

Kang, Y., & Stasko, J. (2012). Examining the use of a visual analytics system for sensemaking tasks: Case studies with domain experts. *IEEE Transactions on Visualization and Computer Graphics*, *18*(12), 2869–2878.

Kim, S. Y., Jang, Y., Mellema, A., Ebert, D. S., & Collinss, T. (2007). Visual analytics on mobile devices for emergency response. In *IEEE symposium on visual analytics science and technology* (pp. 35–42). Sacramento: IEEE.

Kluse, M., Peurrung, A., & Gracio, D. (2012). The evolving leadership path of visual analytics. In J. Dill, R. Earnshaw, D. Kasik, J. Vince, & P. C. Wong (Eds.), *Expanding the frontiers of visual analytics and visualization* (pp. 31–42). London: Springer.

Konecni, S., Grinstein, G., Costello, L., & Byrne, H. (2010). Scenario design for evaluation of visual analytics tools to support pandemic preparedness and response. In *IEEE conference on visual analytics science and technology.*

Liu, C., Ramirez-Serrano, A., & Yin, G. (2011). Customer-driven product design and evaluation method for collaborative design environments. *Journal of Intelligent Manufacturing*, *22*, 751–764.

Lubart, T. I., & Georgsdottir, A. (2004). Creativity: Developmental and cross-cultural Issues. In S. Lau, H. A.N., & G. Y. Ng (Eds.), *Creativity:When east meets west* (pp. 1–32). Singapore: World Scientific.

Luo, H. (2006). Exploring large-scale video news via interactive visualization. In IEEE symposium on visual analytics science and technology (pp. 75–82).

Luo, D., & Ghoniem, M. (2007). NewsLab: Exploratory broadcast news video analysis. In *IEEE symposium on visual analytics science and technology* (pp. 123–130).

MacDonald, C. M. (2012). *Understanding usefulness in human-computer interaction to enhance user experience evaluation.* Doctoral dissertation, Drexel University.

MacEachren, A. M., Jaiswal, A., Robinson, A. C., Pezanowski, S., Savelyev, A., Mitra, P., et al. (2011). SensePlace2: GeoTwitter analytics support for situational awareness. In *2011 IEEE conference on visual analytics science and technology (VAST)* (pp. 181–190). IEEE.

Maciejewski, R., Kim, S., King-smith, D., Ostmo, K., Klosterman, N., Mikkilineni, A. K., et al. (2008). Situational awareness and visual analytics for emergency response and training. In *IEEE conference on technologies for homeland security* (pp. 252–256).

Maciejewski, R., Rudolph, S., Hafen, R., Abusalah, A. M., Yakout, M., Ouzzani, M., et al. (2010). A visual analytics approach to understanding spatiotemporal hotspots. *IEEE Transactions on Visualization and Computer Graphics*, *16*(2), 205–220.

Maciejewski, R., Tyner, B., Jang, Y., Zheng, C., Nehme, R. V., Ebert, D. S., et al. (2007). LAHVA: Linked animal—human health visual analytics. In *IEEE symposium on visual analytics science and technology* (pp. 27–34). IEEE.

Malik, A., Maciejewski, R., Maule, B., & Ebert, D. S. (2011). A visual analytics process for maritime resource allocation and risk assessment. In *2011 IEEE conference on visual analytics science and technology (VAST)* (pp. 221–230). IEEE.

Mane, K. K., Bizon, C., Schmitt, C., Owen, P., Burchett, B., Pietrobon, R., et al. (2012). VisualDecisionLinc: A visual analytics approach for comparative effectiveness-based clinical decision support *in psychiatry. Journal of Biomedical Informatics*, *45*(1), 101–106.

Plaisant, C., Grinstein, G., Scholtz, J., Whiting, M., O'Connell, T., Laskowski, S., et al. (2008). Evaluating visual analytics at the 2007 VAST symposium contest. *IEEE on Computer Graphics and Applications*, *28*(2), 12–21.

Reddy, R., Höferlin, M., Dambier, M., & Weiskopf, D. (2012). Visual analytics for dynamic evacuation planning. In *Proceedings of EuroVA 2012: International workshop on visual analytics* (pp. 13–17).

Rudolph, S., Savikhin, A., & Ebert, D. S. (2009). FinVis: Applied visual analytics for personal financial planning. In *2009 IEEE symposium on visual analytics science and technology* (pp. 195–202). IEEE.

Savikhin, A., Fraser, S., Fisher, B., & Ebert, D. S. (2011). An experimental study of financial portfolio selection with visual analytics for decision support. In *44th Hawaii international conference on system sciences (HICSS)* (pp. 1–10).

Savikhin, A., Maciejewski, R., & Ebert, D. S. (2008). Applied visual analytics for economic decision-making. In *2008 IEEE symposium on visual analytics science and technology* (pp. 107–114). IEEE.

Scholtz, J. (2006a). Beyond usability: Evaluation aspects of visual analytic environments. In *IEEE symposium on visual analytics science and technology* (pp. 145–150).

Scholtz, J. (2006b). Metrics for evaluating human information interaction systems. *Interacting with Computers*, *18*, 507–527.

Shrinivasan, Y. B., Gotzy, D., & Lu, J. (2009). Connecting the dots in visual analysis. In *2009 IEEE symposium on visual analytics science and technology* (pp. 123–130). IEEE.

Soban, D. S., Salmon, J., & Fahringer, P. (2011). A visual analytics framework for strategic airlift decision making. *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology.*

Stemler, S. (2001). An overview of content analysis. *Practical Assessment, Research and Evaluation*, *7*(17), 137–146.

Stoffel, A., Zhang, L., Weber, S. H., & Keim, D. A. (2012). AMPLIO VQA—A web based visual query analysis system for micro grid energy mix planning.

Thomas, J., & Cook, K. (2005). *Illuminating the path: The research and development agenda for visual analytics*. Los Alamitos, CA: IEEE Computer Society.

Thomas, J., & Cook, K. (2006). A visual analytics agenda. *IEEE on Computer Graphics and Applications*, *26*(1), 10–13.

Tintarev, N., & Masthoff, J. (2012). Evaluating the effectiveness of explanations for recommender systems. *User Modeling and User-Adapted Interaction.*

Tullis, T., & Albert, W. (2008). Measuring the user experience. In *Measuring the user experience: Collecting, analyzing, and presenting usability metrics* (pp. 142–144).

Wang, X., Charlotte, U. N. C., Bier, E. A., & Ribarsky, W. (2011). A two-stage framework for designing visual analytics system in organizational environments. In *IEEE symposium on visual analytics science and technology* (pp. 251–260).

Weaver, C., Fyfe, D., Robinson, A., Holdsworth, D., Peuquet, D., & MacEachren, A. M. (2007). Visual exploration and analysis of historic hotel visits. *Information Visualization, 6*(1), 89–103.