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A Survey on the Role of Individual Differences on Visual Analytics Interactions

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***Abstract*—There is ample evidence in the visualization community that individual differences matter. These prior works highlight various traits and cognitive abilities that can modulate the use of the visualization systems and demonstrate a measurable influence on speed, accuracy, process, and attention. Perhaps the most important implication of this body of work is that we can use individual differences as a mechanism for estimating people's potential to effectively leverage visual interfaces or to identify those people who may struggle. As visual literacy and data fluency continue to become essential skills for our everyday lives, we must embrace the growing need to understand the factors that divide our society, and identify concrete steps for bridging this gap. This paper presents the current understanding of how individual differences interact with visualization use and draws from recent research in the Visualization, Human-Computer Interaction, and Psychology communities. We focus on the specific designs and tasks for which there is concrete evidence of performance divergence due to individual characteristics. The purpose of this paper is to underscore the need to consider individual differences when designing and evaluating visualization systems and to call attention to this critical future research direction.**

***Index Terms*—visualization, individual differences, personality, locus of control, cognitive abilities**

I. Introduction

A substantial amount of work has been done to uncover the effects that individual differences have on visualization interactions. The implications of this research are attractive and far-reaching; with a profound understanding of this relationship, we could design visualizations catered to a person's specific needs, and infer a person's traits from their interactions with electronic media. However, there is still much work to be done, the nature of which is not always immediately clear.

The task of surveying the role of individual differences on visual analytics interactions is a very open-ended problem. There are many ways to taxonomize this research, such as by by individual trait or experimental design. However, the distribution of research effort is uneven; there is far more research focusing on certain individual traits, such as locus of control, than others, such as openness. As such, a taxonomy that simply enumerates the work done for each trait would be limited. Instead, we use the well-understood traits to contextualize the state of research for all other traits to gain clearer insight into productive avenues for future research.

Boeing: Integrated Computational and Cognitive Workflows for Improved Security and Usability
DOD: Investigating the Role of Individual Differences in Visual Analytic Workflows

The well understood traits that we examine are locus of control, perceptual speed, visual working memory, verbal working memory. We refer to these latter three traits under the collective umbrella of ”cognitive traits”, because a significant amount of research has evaluated them together. By tracking the progression of research for these two groups, and discussing their roles in visual analytics interactions, we can more accurately discuss the states of other individual differences. The other traits we consider include the Big Five personality traits of Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism. These traits are often studied in aggregate, and can be measured reliably with the International Personality Item Pool. However, each study surveyed has only been able to discover significances for a subset of these traits, and our understandings of specific traits' effects varies significanly.

Fifty seven visualization papers have been surveyed, and twelve of these papers have been found to directly examine the relationship between visual analytics interactions and the individual traits enumerated above. These twelve papers, and the traits that they assessed, are shown in Figure 1

A. Visual Analytics Interactions

It is worth noting that an interaction with a visualization is not well defined. As such, a visualization study has endless ways to measure and interpret an interaction. However, the majority of studies surveyed have asked participants to use a visualization to answer questions about the information portrayed, where response accuracies serve as metrics for how ”well” an interaction went. While these questions are usually structurally similar, they have been taxonomized in multiple different ways. One such taxonomy names questions as either procedural or inferential [5]. Procedural tasks are defined as those that can, with repetition become automatic and require little conscious focus. Inferential tasks are those which require a person to draw conclusions from the information available to them. Although question-based encodings enjoy the benefits of being qualitative and consistent, they is provides a limited view of the interactions themselves. Other methods of measurement include tracking eye movement, time, and mouse movements as a person interacts with a visualization [2], [5]. Each different encoding may reveal a different perspective with which to examine an interaction. As such, with traits for which the majority of studies have relied on question accuracies in their

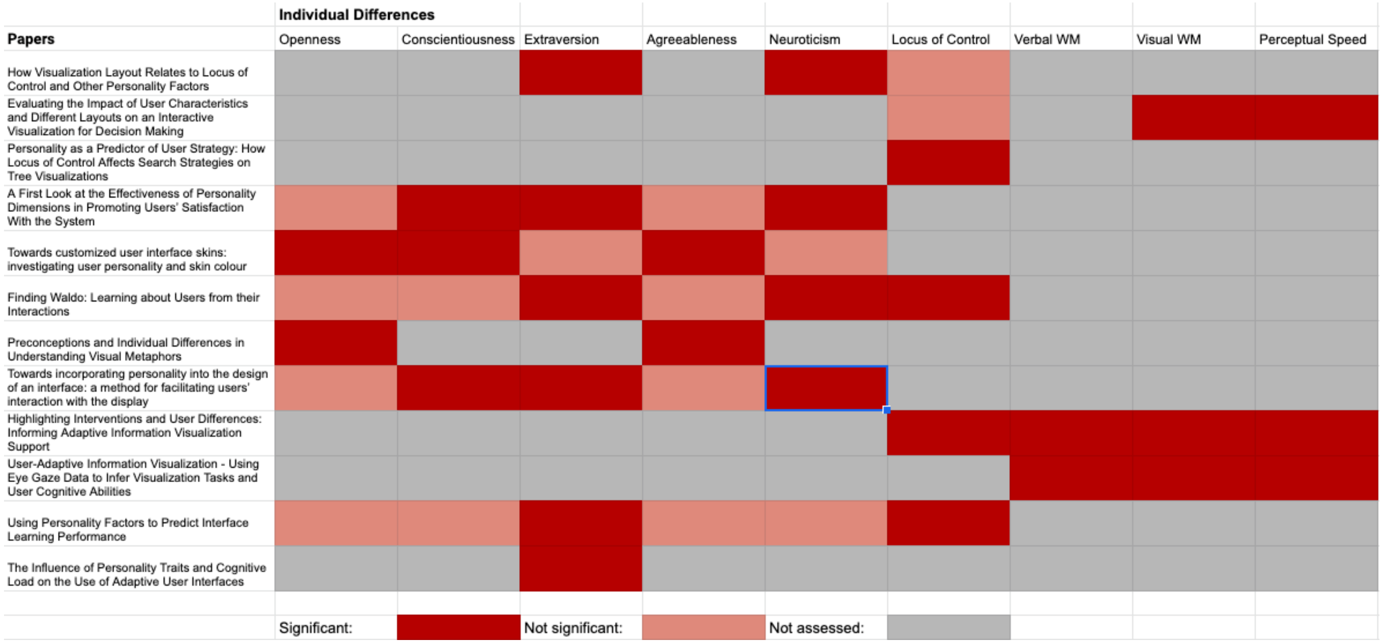

Fig. 1. Heatmap of individual differences-visualization papers and the traits they found significant.

assessment of interactions, it would be productive to explore interactions with a more diverse set of encodings.

II. Locus of Control

Locus of Control, the degree to which a person believes they have control over their lives, has been studied closely within the context of visualization. Green et al's "Using Personality Factors to Predict Interface Learning Performance" was a seminal work in this effort. In this study, participants were asked to complete personality inventories to assess their degrees of locus of control, anxiety, neuroticism, extraversion, self-regulation, and tolerance of ambigiuty. They then familiarized themselves with two real-world visualizations of the same dataset: a row-based representaiton, and a pictoral, container-based representaiton. Particpants then used these visualizations to answer a series of procedural and inferential tasks, and their answers were analyzed with respect to each measured personality trait. Significant correlations were found for the traits of locus of control and anxiety, specifically that those with an external locus of control tended to complete inferential tasks more quickly, and those with greater anxiety measures tended to complete iterative search tasks more quickly [5]. These results suggested that the effects of individual traits on visualization interactions varied with the manner and purpose of these interactions.

Since Green et al's study, Locus of control, and individual differences in general have been studied with greater attention to the precise nature of given visualizations and tasks. Ziemkiewicz et al's 2011 study, "How locus of control influences compatibility with visualization style" assessed both procedural and inferential tasks, while examining individual differences with a more isolated assessment of layout. This study evaluated locus of control with four visualizations of increasingly explicit containment metaphors. These metaphors ranged from simple indentations to mark hierarchy to series of nested boxes. It found that those with external locus of control answered questions on the most and least explicit metaphors faster, and performed better than those with internal locus of control in general. There were no response time differences observed for those with average locus of control. Search tasks also produced no significant differences in response time across visualizations and participants [10]. This study was a progression on Green's because it isolated visualization layout in its study of individual traits, while reinforcing the idea that the types of tasks performed (eg procedural vs inferential) affect interactions nonuniformly.

At this point, there was substantive evidence that locus of control impacted visualization interactions with respect to layout structure and tasks performed. Ottley et al's 2012 study, "Priming Locus of Control to Affect Performance", extended this research by examining if Locus of Control could be "primed" before visualization interaction. People were asked to recall situations in which they felt in control or out of control, before participanting in a replication of Ziemkiewicz's 2011 study. Ottley et al found that peoples' Locus of Control could be "swayed" externally or internally, which was reflected in the replicated study's results [7]. The idea that individual traits, which are often thought to be static, can be influenced carries powerful implications. As the personality-visualization relationship becomes more well understood, whether traits can be primed to provoke specific interactions with a given visualization may become a relevant question.

In a return to direct application, Brown et al's 2014 study, "Finding Waldo: Learning about Users from their Interactions" looks at the classic children's game, Where's Waldo. After having their levels of locus of control, extraversion, and neuroticism assessed, participants were asked to find and identify the Waldo character as fast as possible in an image. The image was zoomed in, and so required arrow presses to explore fully. Arrow presses, mouse events, and task completion times were recorded. These recordings were used to develop state based, event based, and sequence based encodings with which to predict personality using machine learning. It was found that all three assessed traits could be predicted from these encodings [2]. This study not only introduced a new task outside of the domain of information retrieval and analysis, but also showed that novel interaction encodings beyond speed and accuracy had promising applications for data analysis.

While these four studies are far from an exhaustive list of work done on locus of control, they do present a robust exploration of its relationship with visualization. Locus of control has been evaluated with respect to a diverse range of tasks, interaction measurement methods, and visualizations. Although more generalized truths about the role of locus of control in visual analytics interactions have not been uncovered, the state of locus of control research is a good reference for other personality traits.

III. Cognitive Abilities

Visual working memory, verbal working memory, and perceptual speed have often been studied with respect to visualization under the collective label "cognitive abilities" [3], [4], [9]. A primary goal of this research is to design individual-sensitive visualizations. If a person's traits could be inferred, visualizations could eventually be catered to that person's specific strengths and needs. Steichen et al's study into cognitive abilities, "User-Adaptive Information Visualization: Using Eye Gaze Data to Infer Visualization Tasks and User Cognitive Abilities" is a useful lense into this effort [9]. This work examines the potential of real time eye-gaze tracking data in extracting information about a person's traits and current activity. Study participants were presented with either a bar or radar graph and asked to answer taxonomized questions about the information displayed. It was shown that by tracking a participant's eye gaze data, researchers could predict not only the type of visualization used, but also the task at hand through observations connected with a user's individual traits. It was found that eye gaze information at the start of an interaction was most useful for predictions. High verbal working memory was correlated with less time fixated on graph textual information, high visual working memory was correlated with lower times until a first fixation, and low perceptual speed was correlated with more time focused on graph legends. These correlations, when observed with eye gaze data, could produce useful real-time visualization adaptations (eg a person with low perceptual speed could be registered in order to produce more accomodating legends.)

Adaptations are further studied with respect to cognitive abilities in Carenini et al's "Highlighting interventions and user differences: Informing adaptive information visualization support." This study examined the effects of real-time adajustments to bar graphs designed to assist in graph comprehension. It was found that these adjustments could aid study participants in question performance. Additionally, this study found that high perceptual speed was correlated with significantly faster task completion, and that low verbal working memory was correlated with worse task performance [3]. A 2014 study on cognitive abilities in the context of user layout found similar results when measuring task completion times. It found that low verbal or visual working memory was correlated with slower sorting times, and perceptual speed was correlated with faster completion times across all tasks [4]. However, this study also examined "high level" questions that consisted of more general, qualitative questions, and found no significant effects of cognitive abilities for these particular questions. While the contexts of each of these three studies varied, the consistency of their results lends credence to an intuivive thought on the impact of cognitive abilities: higher levels of cognitive abilities allow more proficient interactions with visualizations.

Each of these studies had administered questions under the same task taxonomy of "low level" tasks. This taxonomy enumerated questions as forms of information extraction, which belonged to classes such as "Retrieve Value", "Compute Derived Value", and "Sort" [1]. While these classes are far from exhaustive, it is worth noting the standardization with which these studies on cognitive abilities have been administered. This standardization may have contributed to the strong consistency that has been observed for cognitive abilities. It is reasonable that higher cognitive abilities could be particularly well suited suited to the task of extracting information from a visualization. As such, future research efforts may benefit from exploring novel encodings of interaction and higher level tasks.

IV. The Big Five Personality Traits

Personality is often studied in visualization using the Five-factor model, or Big Five personality traits. These traits consist of Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism. While these traits are often evaluated together, our levels of understandings of each trait's impact on visualization interaction varies considerably.

A. *Openness*

Openness to experience is a trait that has not enjoyed much attention. However, it has been shown to imply adaptability in visualization interactions. For example, a 2009 study proposed a framework for studying visualization through the visual metaphors they portray. It compared node-link diagrams and treemaps in their display of information hierarchies, either as series of levels or as sets of nested containers, respectively. Study participants were then asked to answer questions about each visualization, where the questions were phrased with either compatible or conflicting metaphors to their respective visualizations. The study found that this question-visualization compatibility nearly universally impacted the accuracy of participants' responses. The one exception to this effect was observed in people with high levels of openness. This abscence suggests that openness to experience allows easier adjustment to disruptions in visualization interaction. It is worth noting that this example slightly deviates from our framework in that it discusses the impact of openness in terms of a lack of significant observation. As such, it is indicative of a weaker understanding of the relationship between openness and visualization interaction. Nonetheless, this finding seems logical and carries promising implications. Future openness research could benefit from exploring visualization contexts that require participants to interact with more dynamic visualizations and tasks.

B. Extraversion

Extraversion, which is often characterized by outgoing behavior, displays consistent significance within visualization performance. In a study conducted by Sarsam et al, participants were divided into 2 clusters based on their personality profiles. Notably, people with higher scores in extraversion were clustered with those with high scores in conscientiousness, while the other cluster was marked by people with high neuroticism scores. These clusters were then mapped to a set of UI design characteristics using association rules, a popular method for uncovering relationships among variables. When another set of users were asked to evaluate UI designs constructed based on these rules, the cluster they belonged to was shown to reliably predict their preferences for UI design choices [8]. This study is especially significant not only for its evidence towards a relationship amongst personality traits and visual analytic performance, but also for its presentation of concrete design choices. For example, the discovered rules included specific font choices such as Verdana vs Arial, and high vs low information density. These findings present evidence that specific, concrete design choices can be made based on the personality profiles of users, to increase user satisfaction. Brown et al's 2014 study also found that extraversion levels could be predicted from the task encodings, which suggests that different encodings which interact with extraversion could be worthwhile to explore further [2]. Amongst the big five personality traits, extraversion seems the most well studied. However, its research faces similar challenges to those of Locus of control, in that clear, generalized conclusions regarding its interactions with visualizations cannot yet be made. Nonetheless, because extraversion has consistently shown significance in the tasks and interaction measurements of visualization studies, it is reasonable to predict that future evaluations of the big five personality model will continue to uncover effects of extraversion.

C. Neuroticism

Neuroticism, the tendendency to experience negative emotions, has similarly shown consistent significance. As with extraversion, levels of neuroticism have been reliably predicted from novel encodings of interaction [2], and have been the basis for the creation of personalized design rules [8]. Ziemkiewicz's examination of layout with respect to containment metaphors found that high levels of neuroticism were correlated with better task performance on the layouts with most and least explicit containment metaphors [10]. Our understandings neuroticism and extraversion are at similar states in terms of the amount of conclusions that have been reached and the diversity of interaction contexts assessed, so we can expect a similar future progression.

D. Conscientiousness

Conscientiousness which is characterized by carefulness, diligence and discipline, has generally been thought an indicator of success, and has been shown to be positively correlated with academic performance [6]. As such, it may be intuitive to hypothesize that similar effects to those of the cognitive abilities mentioned above would be consistently observed, since most visualization studies have studied conscientiousness with question accuracy as the metric to capture interaction. However, these effects have not been observed. While its effects have been examined with respect to extraversion [8] to discover concrete design choices, it has not shown substantial, isolated significance. It therefore may be productive to assess conscientiousness in isolation, to decorrelate its effects from those of other traits.

E. Agreeableness

Our understanding of the effects agreeableness, which is associated with kindness and modesty, is markedly poor. Out of the fifty seven studies surveyed, it has neither been discussed nor found significant. Because none of the current research has uncovered results, future avenues of research remain unclear. While discussions of agreeableness with respect to visual analytics interactions therefore remain speculative, it is worth considering what apects of visualization studies examined could lead to discoveries for every trait examined except agreeableness. Within each study, none of the tasks that participants are asked to perform have intuitive connections to agreeableness. Moving forward, it may be productive to design studies that examine more intuitively relevant tasks. For example, if a visualization portrayed two conflicting beliefs sympathetically, and evaluated participant preferences towards each belief, would a person with high measures of agreeableness exhibit a marked openness towards both?

V. Conclusions

This survey is meant to reflect the current state of visualization research with respect to individual traits. While the results observed from these traits vary significantly, there are many avenues of future research available for each one such that we explore them with respect to a robust evaluation of different interactions and visualizations.

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